Impact of Increased ICT Latency on Active Distribution Network Control

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***Abstract*—With regard to the ongoing changes in modern power systems towards increasingly decentralised systems, the coordination of generation assets and the corresponding dependency on Information and Communication Technology (ICT) becomes highly relevant. This work demonstrates the impact of varying ICT latency on the control and the behaviour of Distributed Energy Resources (DERs) in an exemplary medium voltage grid. Thereby, the focus is on the settling time, the overshooting and the stability of the active power flow control between the interface of the medium and high voltage grid. Furthermore, this work describes a general method to simplify and analyse the stability of distribution networks with high DER-penetration, especially their sensitivity towards communication latency between the network controller and the decentralised assets.**

***Index Terms*—Distributed Energy Resources, Active Distribution Network, Latency, Settling Time, Ancillary Services**

I. Introduction

Power systems in Europe, especially Germany are undergoing fundamental changes with, among others, heavy impact on the level of decentralisation. Government incentives lead to the installation of many Distributed Energy Resources (DERs) while big conventional power plants are being decommissioned and both these trends are expected to be continued [1]. This transition from few central power plants that can be directly controlled by grid operators to a decentralised system with many DERs and with usually no means of direct control has implications on the stable operation of the power system. Transmissions System Operators (TSO) control power generation and power flows to keep energy generation and consumption in balance as well as to prevent and manage potential congestions in their networks. Until today, this option is primarily enabled by conventional plants that offer ancillary services in the form of operational flexibility to the TSO [2].

In a decentralised power system, these ancillary services are more difficult to realise though. On the one hand, many generation units are connected to the low or Medium Voltage (MV) levels that are controlled by Distribution System Operators (DSO) and not directly by the TSO. On the other hand, the sheer amount of DERs requires a more sophisticated coordination in order to maintain the required level of performance and efficiency of ancillary services [4]. A prominent method to decrease the complexity of coordination is to cluster the DERs. An easy way to start doing so would be to define distribution networks as such clusters. From a topological perspective distribution grids are in many cases already well defined and comprise the majority of DERs. A TSO could then, for example request a specific power flow from any cluster while the management of each cluster's individual DERs would be conducted by the cluster's own controller. In accordance with [5], this concept of a distribution grid that acts as a cluster of DERs which provides flexibility is labeled as an Active Distribution Network (ADN). Hence, centralised conventional power plants could potentially be replaced by ADNs when it comes to the provision of ancillary services [5]. This concept can be utilised in a variety of situations where the tolerable response of the ADN, in terms of settling time and overshoot, lies within seconds to minutes, such as:

- Reactive / curative redispatch
- Frequency control (via provision of active power control by the underlying ADNs)
- Voltage control in Transmission Systems (via provision of reactive power control by the underlying ADNs)

The coordination and control of DERs in an ADN requires communication between the controller and the DERs and the detailed requirements for such Information and Communication Technology (ICT) are already well known for higher voltage grids. In contrast to that, the future dependency of lower voltage grids on ICT is a rather new topic since so far only very limited information is being generated and transferred in these grids. Without additional research the increasing penetration of ICT in power systems might thus

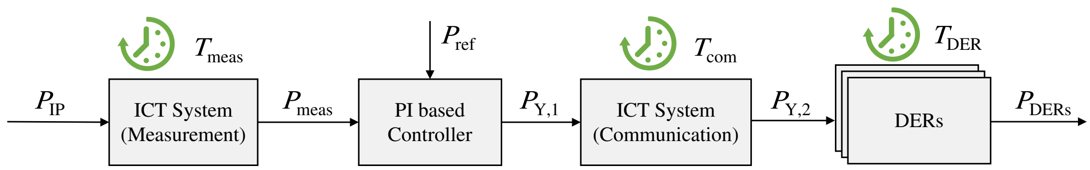

Fig. 1. Structure diagram with focus on latency in the control system model based on [3]

lead to potential new risks. One major disadvantage of ICT-reliant control mechanisms is the ICT system's latency, its variations and stochastic behaviour add to the complexity of the controller [6]–[8]. Therefore, this work analyses the impact of varying ICT latency on the behaviour and stability of DER-clusters based on an exemplary ADN control proposed in [3].

The paper is structured as follows: After an initial literature review in section II, the adapted ADN simulation model of [3] is described in detail in section III. In section IV the influence of latency on the behaviour of the modelled ADN is investigated by means of time domain simulations.

II. Related Work

In order to coordinate a large number of DERs in distribution grids, many automated control methods have been researched to regulate the power flow at the interconnection point (IP) between two voltage levels, especially at the IP between the distribution and transmission grids [3], [5], [9]–[11]. Basically, the control methods can be differentiated by the time frame of operation. In [10] and [11], a management system and a framework based on optimization, with the focus on the interface between distribution and transmission system is proposed. In both approaches, the control of distribution grids is based on scheduling DERs with a resolution of 15 minutes, and therefore ICT latency is less important for these concepts. Whereas, the concepts in [3], [5], [9] enable a fast real-time control of the active and reactive power flow at the voltage level interface by controlling a large number of DERs connected to the distribution system. The works of [9] and [5], describe a system for power flow control at the IP between High Voltage (HV) and MV grids. In contrast to [9] and [5], [3] shows a hierarchical control scheme that focuses on the active power flow control at interface of the Extra High Voltage (EHV), HV and MV. These fast real-time control concepts include ICT systems to exchange information between a control system and DERs. In [12] and [13], the impact of communication latency on the bus voltages of centrally controlled micrograds has been investigated. Furthermore, [14], [15] demonstrate the positive impact of Software-Defined Communication Networks on the critical sensitivity of Multi-Agent based distribution grid control towards ICT latency. The analysis of delayed measurement and control-data on the control systems in [3], [5], [9] is still at an early research phase and therefore, is addressed in this work. This paper also contributed towards more fundamental research works on critical interdependencies between future power and ICT systems as described in [16] by providing detailed simulation results for an exemplary cyber-physical energy system. Furthermore, the focus of this paper is on the active power control. In [9] and [5] it could be shown that the control of the reactive power is possible in the same way.

III. Simulation Model

This section describes the MATLAB Simulink simulation models used in this work to evaluate the impact of ICT latency on a control system based on [3]. A detailed model of an ADN is first presented in this section. The explanation of this model starts with a general description of the control system from [3]. In comparison to [3], a more detailed ICT system is added for the studies in this paper, which are subsequently described in detail. Additionally, the grid model used as well as the simulation parameters are briefly outlined. At the end, a simplified Linear Time-Invariant (LTI) system model of the ADN is presented, which allows the use of well-established methods to investigate the stability.

A. Structure and Functionality of the control system

In comparison to [3], only one 20 kV MV grid is considered in this work. The control system in [3] enables ADNs to follow power flow setpoints at the IP to the next higher voltage level by controlling a large number of DERs. Fig. 1 shows a brief overview of the control system. The control system measures the power flow at the IP (P_{IP}) between the HV and MV grid. The measurement part of the ICT system includes a measurement latency T_{meas}. Based on the measured power flow P_{meas} and a reference variable P_{ref} a PI controller determines a correcting variable $P_{\mathrm{Y,1}}$, which is then transmitted via the communication part of the ICT system to the DERs connected to the distribution grid. The communication part of the ICT system includes a latency T_{com}. The DERs then adjusts their active power output P_{DERs} depending on the correcting variable $P_{\mathrm{Y,2}}$, so that P_{IP} follows P_{ref}. The DERs react after the delay T_{DER}. In summary, the total latency is described by

$$T_{\mathrm{total}} = T_{\mathrm{meas}} + T_{\mathrm{com}} + T_{\mathrm{DER}}. \quad (1)$$

The delay T_{DER} remains constant, where T_{meas} and T_{com} are varied in the simulations presented.

B. Measurement and Communication System

In order to analyse the impact of latencies on the performance of the control of ADNs a more detailed ICT model

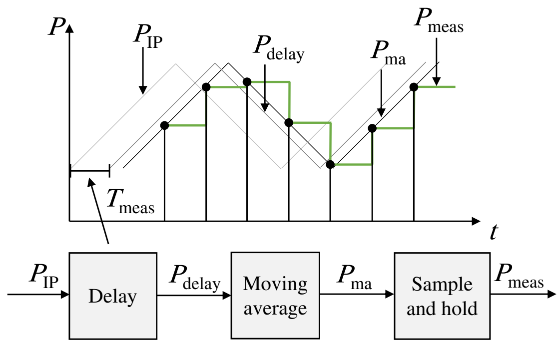

Fig. 2. ICT system (measurement part) with exemplary time course of intern signals

is added to the control system model of [3]. The ICT model consist of a measurement and a communication part, which are equally designed. Fig. 2 illustrates the ICT system model using the measurement part as example. It consists of three blocks - delay, moving average, and sample and hold. The moving average block is described by (2) and Table I.

$$P_{\text{ma}}(t) = \frac{1}{T_{\text{sw}}} \int_{t-T_{\text{sw}}}^{t} P_{\text{delay}}(t)dt \qquad (2)$$

Finally, the sample and hold block takes samples of the output signal of the moving average block with a sample time T_{sh}. Packet errors or dropouts aren't explicit considered in this model. Packet errors as well as dropouts lead to additional delays [8]. Therefore both effects can be depicted by an increasing delay in this model.

C. Test System and Simulation Parameters

The proposed control scheme presented in [3] is tested in the rural 20 kV SimBench benchmark network, which is described in [17]. The considered 97-bus distribution network based on a rural grid, is connected via one IP to a 110 kV transmission grid. Fig. 3 shows an overview of the network topology of the used benchmark system.

The network has a radial structure. The upstream 110 kV grid is modeled as an ideal voltage source. Furthermore, loads are modeled as constant impedances. For lines the three-phase section line model from Simscape Power Systems has been

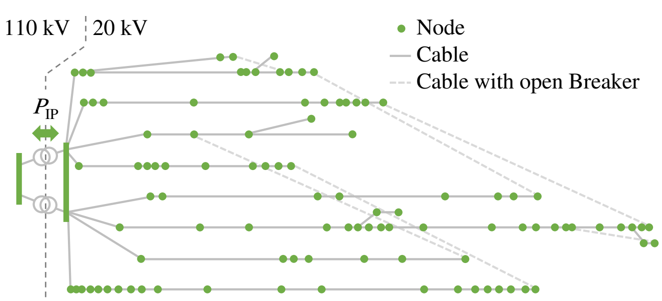

Fig. 3. SimBench 20 kV rural benchmark grid

used. The DERs are depicted with the model described in [5], which consist of a delay, a first order lag, a limiter and a 3-phase controlled current source, which is described in [18]. The total load connected to the grid amounts to 16.79 MW and the total installed generation capacity amounts to 50.61 MW. In the initial state of all scenarios, the total generation in the test system is 33.74 MW, so that the control system has 16.86 MW positive flexibility and 33.74 MW negative flexibility available.

To investigate how latencies influence the dynamic behavior of the modelled system, the measurement and communication latency are varied from 20 ms to 600 ms. The control parameters are kept constant for all simulations of the detailed model. Table I shows an overview of the simulation parameters.

TABLE I
CONSTANT SIMULATION PARAMETERS

Parameter	Value / Characteristic
Simulation Step Size	20 ms
Gain P-Term K_{p}	5.00E-9
Gain I-Term K_{I}	3.21E-8
Initial Power Flow at IP	16.66 MW
Latency DER T_{DER}	0.01 s
Sliding Window Measurement $T_{\text{sw}}^{\text{meas}}$	0.1 s
Sliding Window Communication $T_{\text{sw}}^{\text{com}}$	0.2 s
Sample time Measurement $T_{\text{sh}}^{\text{meas}}$	0.1 s
Sample time Communication $T_{\text{sh}}^{\text{com}}$	0.2 s

The test system is implemented in the Simcape Power System simulation environment using phasor simulation method and Heun's integration technique.

D. Simplified LTI System Model for Stability Analysis

In order to analyse specifically the stability of the ADN with regard to communication latency and a focus on eigenvalues of the test system, a simplified LTI system model of the ADN has been developed and validated for this work. The structure of the LTI system is depicted in Fig. 4. The grid model is not considered in the LTI system. Furthermore, the control system is only represented by a PI-controller. The sum of all DERs are approximated by one first order transfer function, where K_{DERs} is set to 33.74E6 and T_{DERs} is set to 0.1 s. In contrast, the total load P_{Load} is assumed to be constant. The total delay of the test system is summarised by $T_{\text{total,LTI}}$. In addition to T_{total}, $T_{\text{total,LTI}}$ includes a further delay of 0.3 s, which represents the moving average and sample and hold blocks of the ICT system described in Fig. 2. In order to determine the eigenvalues of the closed loop system in Fig. 4, the total delay of the LTI system $T_{\text{total,LTI}}$ is approximated by a third order transfer function. An exemplary simulation result of the LTI system in the time domain is shown in Fig. 5.

IV. SIMULATION RESULTS

The simulations were done considering load jumps in the ADN and setpoint changes for desired active power flow (P_{ref}) at the IP. The jumps were considered in both positive and negative directions. The simulations were done with variable measurement and communication latency and explicit control parameters.

An exemplary simulation result is depicted in Fig. 5. Here, a positive 5 MW jump of the desired active load flow at the IP is simulated with a total communication latency of 0.81 s. This total latency consists of a measurement latency and a control data delay of 0.4 s each, plus the latency T_{DER} of 0.01 s. The settling time, with a tolerance of 5 % for this scenario, is 12.4 s. Furthermore, the sampling effect of the modeled measurement equipment is visible.

A. Settling time

Initially, the simulation results are in agreement with the hypothesis about the correlation between communication latency and ADN's settling time after a load jump or a jump in the setpoint P_{ref}. Fig. 6 demonstrates that an increasing ICT latency will first increase the settling time and in more extreme cases, even lead to instabilities in the ADN control. Table II and Fig. 7 show the settling time of different jumps for varying communication latency. Several observations can be made in this regard:

- The overall correlation between the ADN's settling time and the communication latency follows a strong exponential trend.
- The direction of jumps does not have any impact on the settling time or the system stability.
- The nature of the jump (P_{ref} or load) has no significant impact on the settling time with one exception - in cases with increased measurement latency, the controller can only start to compensate after the first abnormal measurement is received. This does not lead to significant differences in these simulations. However, this effect has to be kept in mind when designing control schemes for DERs with regard to communication latency. Furthermore, this effect can be observed especially in the LTI system, where the total system latency is aggregated in one delay.
- The measurement latency's share of the total communication delay has a negligible influence on the settling time and stability. This can be seen in the two simulations with a total latency of 0.52s in Table II (rows marked with *). The minor differences observed can be explained by the exception described in the previous point. In general, this observation in this point legitimizes to summarize the entire system latency in the LTI system.

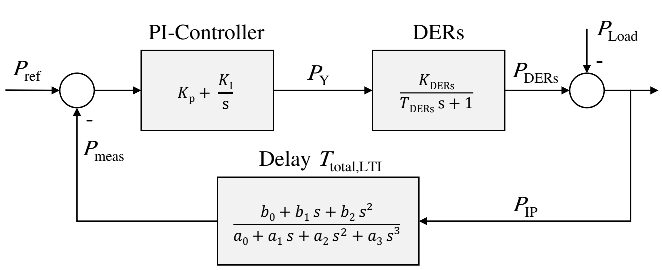

Fig. 4. Structure of the LTI system

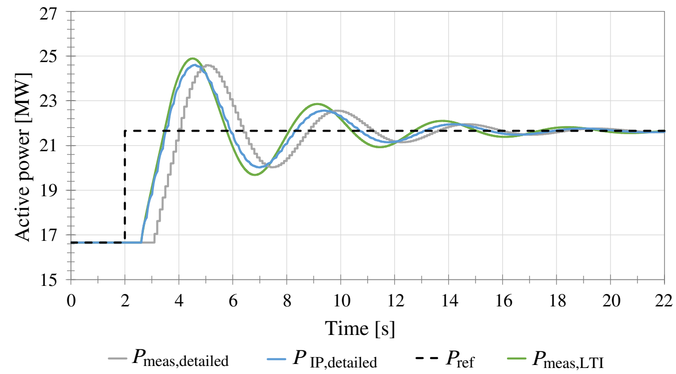

Fig. 5. Response of active power after a +5MW P_{ref} jump at 0.81 s total latency

- The size of the initial jump only has a minor influence on the settling time. For scenarios with generally high latency, the transition phase from a stable system to a system with extreme settling time is shorter for load or P_{ref} jumps.

B. Overshoot

Fig. 8 shows the dynamic overshoot of the ADN towards various jumps in load and P_{ref}:

- Similar to the settling time, the overshoot is dependent on the accumulated latency rather than the individual measurement and communication latency.
- However, in contrast to the settling time, the overshoot shows similar linear behaviour for both load and P_{ref} jumps. This linear behaviour can also be seen in Fig. 8.
- In contrast to the settling time, the overshoot of the system is not significantly affected by the size of the initial jump.
- The results also show that the type of jump has a significant impact on the overshoot of the system.
- Furthermore, it can be observed that for a same jump size, the overshoots are slightly higher for load jump than the P_{ref} jump. This effect grows more obvious with increasing latency.

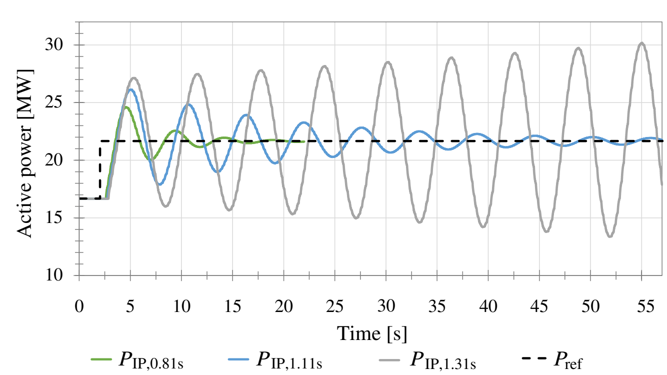

Fig. 6. Active power response to a +5 MW jump of P_{ref} with regard to varying communication latency

TABLE II
IMPACT OF VARYING LATENCY AND JUMP-TYPES AND HEIGHTS ON THE ADN SETTLING TIMES

Latency [s]			Settling Time [s]						
T_{total}	T_{meas}	T_{com}	Load +2 MW	Load +5 MW	P_{ref} +2 MW	P_{ref} +5 MW	P_{ref} -2 MW	P_{ref} -5 MW	P_{ref} +9 MW
0.05	0.02	0.02	2.18	2.16	1.39	2.06	1.64	1.88	2.07
0.21	0.10	0.10	1.66	1.66	1.45	1.45	1.44	1.44	1.46
0.41	0.20	0.20	3.26	3.28	3.00	3.03	2.99	2.97	3.01
0.52*	0.50	0.01	5.22	5.23	4.62	4.62	4.62	4.62	4.64
0.52*	0.01	0.50	5.18	5.21	5.11	5.11	5.11	5.11	5.13
0.61	0.30	0.30	7.36	7.42	6.73	6.71	6.75	6.74	6.79
0.71	0.35	0.35	10.57	9.80	7.78	7.77	7.77	9.21	9.40
0.81	0.40	0.40	11.43	13.25	12.52	12.42	12.60	12.74	12.94
0.91	0.45	0.45	18.87	19.11	18.31	18.48	18.29	18.31	18.87
1.01	0.50	0.50	32.97	30.99	27.72	33.35	27.51	32.94	30.31
1.11	0.55	0.55	49.38	53.22	48.43	51.98	41.23	51.22	60.06
1.21	0.6	0.60	134.25	> 250	136.46	> 250	162.85	156.76	> 250

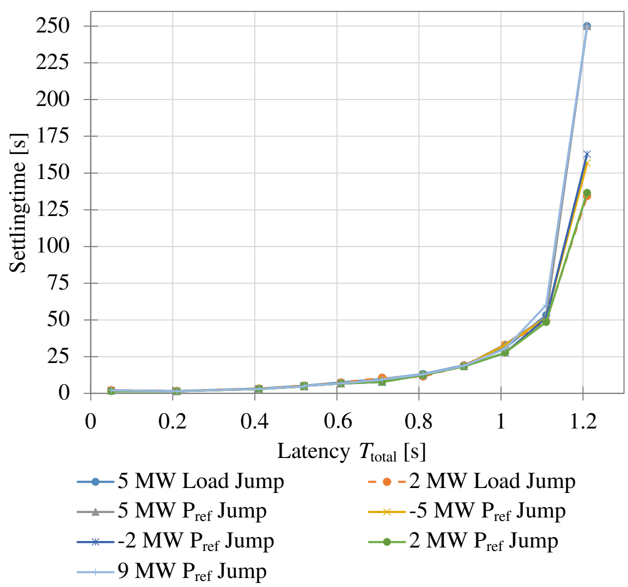

Fig. 7. Comparison of settling times of different load- and P_{ref} jumps with regards to varying ICT latency

C. Stability Analysis using the LTI System

In order to get a better understanding of the influence of latency on the control system of ADNs, the simplified LTI system of the ADN is analysed with regard to its stability. For this purpose, the eigenvalues of the closed loop control are determined by varying the total latency $T_{\text{total,LTI}}$. The results are presented in Fig. 9. As long as the real part of every pole of the transfer function is negative, the LTI system is stable. Fig. 9 shows that the poles move in the direction of the positive half-plane as the total delay $T_{\text{total,LTI}}$ increases. From a delay higher than 1.49 s, two eigenvalues have a positive real part and hence, the system is unstable. Comparable observations can be found in the more detailed model of ADN's. Taking into account the delay of 0.3 s caused by the approximation of the sample and hold as well as the moving average blocks, $T_{\text{total,LTI}}$ of 1.49 s corresponds to a delay T_{total} of 1.19 s in the detailed model. The detailed model becomes unstable at a delay T_{total} of higher than 1.3 s. The lower critical latency clearly demonstrates the lower sensitivity to changes in latency of the detailed model. The discrepancy between the LTI system and the detailed model can be explained by the voltage dependence of the loads and the line losses, which are only considered in the detailed model. The voltage dependence of the loads and the line losses have a dampening effect on the system behaviour. If the control system is designed using the LTI system, there is an additional buffer up to the stability limit. Due to this reason the determination of the eigenvalues of the proposed simplified LTI system is an easy and suitable method to analyse the stability considering ICT latency in future ADNs and to define proper controller parameters. In a further analysis, beginning with a total latency of $T_{\text{total,LTI}}$ = 4 s, the parameters K_{I} and K_{P} were gradually reduced. By reducing the size of K_{I} and K_{P}, the critical poles return to the negative half-plane making the system stable. Reducing K_{I} and K_{P}, however, has the consequence that the system has significantly higher settling times.

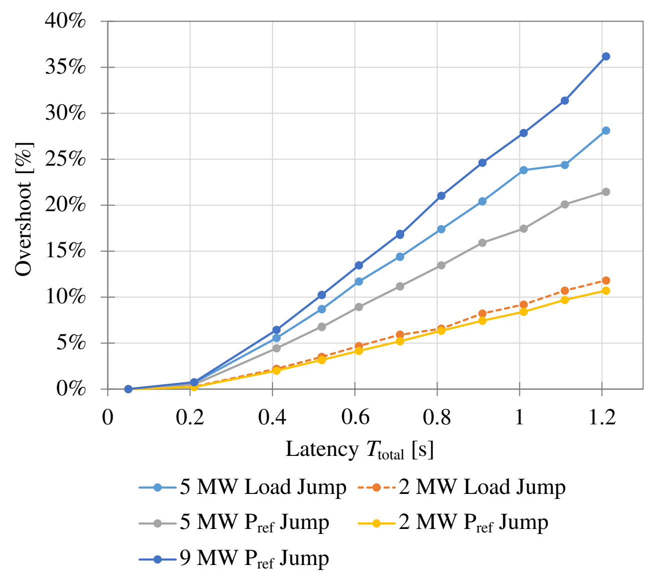

Fig. 8. Comparison of overshoot behaviour of different load- and P_{ref} jumps with regards to varying ICT latency

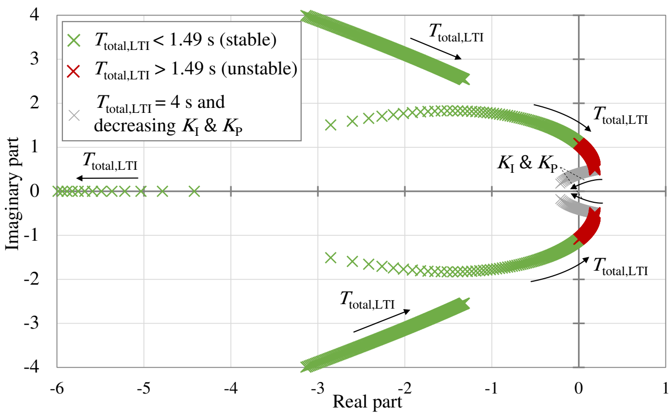

Fig. 9. Root locus by varying $T_{\text{total,LTI}}$, K_I and K_P

V. Conclusion & Outlook

This work presents the results of the exemplary ADN control with varying ICT latency. It shows a significant correlation among the latency, settling time and the overshoot in the behaviour of DER-clusters. The corresponding behaviour of settling times follows an exponential trend and therefore, shows that there is a critical threshold of ICT latency beyond which an ADN quickly turns unstable with regard to its response to a load jump or a change in the desired setpoint. This can possibly render the affected ADN incapable of providing the formerly described ancillary services for TSOs until the latency returns to an acceptable level. Choosing different controller parameters would result in a trade-off between more robustness to higher latency and faster settling times. Another important result is the irrelevance of how the total latency is divided between measurement latency and the delay of control data. This insight is important for the proposed method of simplifying and analysing an ADN's sensitivity towards ICT latency by aggregating all DERs and neglecting the power grid. This method helps to transform the task of designing ICT-reliant controllers for ADNs from a complex multi-domain problem into a basic controller design problem. A comparison between the detailed simulation of an ADN and the results of the proposed simplified approach proves that the proposed approach can potentially provide comparable results under certain circumstances. The minor differences between the results of the two approaches can be explained by the fact that voltage-dependent loads and losses on the lines are considered in the detailed simulation but ignored in the simplified approach.

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