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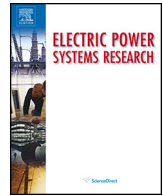
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Overlaying control mechanism for solar PV inverters in the LV distribution network



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ABSTRACT

Increasing penetration of distributed renewable energy sources in LV grid leads to a number of power quality challenges. Meanwhile, changes in recent renewable energy-related grid codes foresee the massive introduction of remotely controllable inverters in the LV grid. In this paper, the future grid scenario is taken under consideration, thus proposing a solution for overvoltage problem while taking advantage of such controllable inverters. The paper discusses a novel approach to mitigate overvoltage problem by integrating the concept of P - V droop control into a cyber-physical paradigm. The proposed approach introduces a parameter, referred as virtual maximum power point that enables the proposed solution to mitigate overvoltage problem only by using local measurements. Above all, the proposed approach prevents any new hardware-related changes in the inverters. This paper simulates the proposed approach using a co-simulation model. However, to speed up the field implementation of the proposed approach, laboratory experiments were conducted and the solutions for the challenges in real-life implementation, including ICT-related challenges, are developed. Lastly, this paper discusses about the outcomes of the proposed approach in the light of both the theory and practical. In addition to the proposed overvoltage mitigation solution, the possibilities of using the controllable inverters for additional network services are also discussed.

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1. Introduction

The ageing distribution network is designed for unidirectional power flow from centralized power generations to customers. The increasing penetration of distributed renewable energy resources (DRES) in the ageing distribution network may lead to bidirectional power flow and may cause power quality problems such as voltage violations, protection blinding, frequency instability, and also other network issues e.g. the overloading of network assets [1,2]. In LV network, although one of the most basic ways to prevent these problems is limiting any additional DRES penetration, it is not an effective approach to solve the aforementioned power quality problems. Another way to mitigate these problems is to control the output power of DRES during the time of network issues, thus such an approach will allow further penetration of DRES in LV network. In this paper, overvoltage and transformer overloading (due to reverse power flow) problems are mitigated by limiting the

output power of DRES. One can inquire that is it allowed to control the output power of DRES under any circumstances. In this regard, the new grid standards and codes such as IEEE 1547, IEEE 929, and German-Erneuerbare-Energien-Gesetz (EEG) have been introduced to increase the penetration of DRES in the distribution network while maintaining the power quality standards [3–5]. In particular, EEG provides a possibility to control even a smaller solar photo-voltaic (SPV) system remotely, which includes roof-top scale SPV units smaller than 3.68 kVA [6]. As new DRES interconnection standards and grid codes allow the remote control capability in the DRES inverter, it would create a trend for the massive integration of controllable inverters (CIs) into LV networks.

A considerable number of solutions have been developed to mitigate the overvoltage problem in LV network, such as cable reinforcement [7], on-load tap changer [8], reactive power control [9], and active power curtailment [10]. As discussed in [11], due to high R/X ratio in LV networks, the solution-based on the active power curtailment is more effective in LV networks. Furthermore, in [12–15], active power-based solutions such as storage, demand response and DRES curtailment were developed to mitigate the overvoltage problem. In order to solve this problem, a typical active power-based solution known as P - V droop control was investigated by several researchers [16–18], which limits the

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output power of DRES proportional to voltage rise at the point-of-connection of DRES inverter. Although these researchers assumed that P - V droop control are embedded in the hardware-level of inverter, the commercially available inverters are not equipped with such feature. Hence, these solutions cannot be implemented in real-life immediately. Thus, in order to mitigate overvoltage problem in real-life, a new control mechanism that uses commercially available CIs is required. Moreover, as it can be recalled, new grid standards and codes allow remote control of CIs. Therefore a new scalable, open architecture-based and easily implementable control algorithm need to be developed to exploit the remote control capability of CIs.

In [19], the overvoltage problem is mitigated by controlling reactive power of an inverter, whereas in [18], the overvoltage problem is mitigated by controlling the active power output of inverters. However, in [20], the voltage violation problem is mitigated by controlling reactive power of all the inverter equally. Moreover, in [21–24], both active and reactive power controls are used for mitigating power quality problems. Similarly, in [25], a novel control approach is proposed for unified control of active and reactive power to mitigate the overvoltage problem. In addition, in [26,27], SPV inverters are controlled to mitigate voltage unbalance in the LV networks. In [28,29], distributed power generation is controlled in order to mitigate transformer overloading. Although extensive studies are carried out in the area of the overvoltage mitigation using SPV inverters [16–29], SPV inverter manufacturers might be reluctant to incorporate new solutions into their inverter design due to following: (i) if a control is embedded in SPV inverters to mitigate a specific power quality problem, in future, the inverter perhaps cannot be used to mitigate other additional power quality problems. For example, undervoltage mitigation may lead to overloading of transformer due to reverse power flow or unbalance problem; (ii) renewable energy-related grid standards and grid codes does not necessitate the P - V droop control. Therefore, though the P - V droop control creates value for distribution system operator, the solar PV inverter manufacturers do not incorporate it, because it does not create any monetary value for customers yet. Thus, it could create a gap between research and real-life implementation.

Furthermore, information and communication technology (ICT)-based solutions have been developed for overvoltage mitigation. For example, [10,30–32] used the recent ICT advancement such as multi-agent system and internet of things to optimize the LV grid operation. However, there has been no detailed investigation of the challenges in the implementation of aforementioned solutions. In [33], Vandoorn et al. coordinated the droop control using communication however they simplified the communication model, and overlooked the impact of communication delay. In [34], controller area network (CAN)-based communication system was used to coordinate the droop controls, which requires a dedicated communication link among the inverters, thus making the overall infrastructure cost inefficient. Recently in [35], Jianli Pan et al. applied advanced level of ICT for energy optimization. However, they used regression model that limits their solution to the chosen buildings thus it is a tailor-made solution for the targeted case study.

1.1. Paper contributions

A number of research gaps are highlighted in the previous section and the contribution of this paper towards the research gaps are briefed in this section.

- (1) The experimental verification of overlaying control is a proof of concept for exploiting a new opportunity in upcoming CIs (i.e.

remote control capability), which is driven by the new DRES interconnection standards and grid codes.

- (2) The overlaying control allows the maximum power point tracking (MPPT) algorithm of CIs continue to operate while the overlaying control runs simultaneously. The proposed control can be called generic control or model-free control since it only requires the local measurement, which is achieved by using a parameter referred as virtual maximum-power point. Therefore, it can be implemented in any commercially available CIs without any new hardware-related changes either in CIs or in the existing ICT infrastructure.
- (3) Since the proposed overlaying control is realized by an ICT paradigm called multi-agent system (MAS), it inherits the hierarchical architecture of MAS. The MAS paradigm facilitates inter agent communication thus more than one agent can be programmed to mitigate multiple power quality problem. Importantly, since the proposed control is realized by an external MAS programme, the SPV inverter manufacturers can easily reprogram the control algorithm to incorporate new grid support services without any new hardware or firmware-related changes. As a proof of concept, laboratory experiments are conducted to test the overlaying control that is realized using MAS. Thus, this paper reduces the gap between research and real-life implementation.
- (4) As discussed earlier, many research works on the subject of the application of ICT for mitigating power quality problems in LV network are mostly restricted to numerical simulations. Therefore, only limited knowledge is available on the subject of the real-life implementation of ICT-based generic overvoltage mitigation solutions. Hence, in this paper, we have identified the challenges in the real-life implementation of the proposed control e.g. the optimal time interval between power-limiting set points.
- (5) In this paper, the communication delay is included in the numerical simulation. In addition, in this paper, the proposed overlaying control uses the well-known WiFi (IEEE 802.11) ICT infrastructure. It can be noted that the majority of the houses in Europe are equipped with WiFi infrastructure and thus the proposed solution can be implemented without any additional investment on the dedicated ICT infrastructure.

The structure of the paper is as follows: Section 2 formulates the targeted power quality problem, briefs the technical limitation of controllable inverters and explains the proposed overlaying control. Section 3 briefs the numerical verification and discusses the key findings of the simulation. Section 4 discusses the lab setup of the conducted experiment and the key findings. Section 5 explains the challenges in implementation. Finally, Section 6 concludes this research work.

2. Overlaying control

The proposed overlaying control mitigates overvoltage problem provided it is operated in standalone mode i.e. decentralized control. On the other hand, the overlaying control can mitigate overloading problem as well as overvoltage problem provided it is operated in a hierarchical architecture mode. Therefore, in this paper the overlaying control is proposed that considers the combination of decentralized and hierarchical operational modes, thus mitigating overvoltage problem in LV networks and overloading problem at distribution transformer.

Firstly, in this section, the objective problem is mathematically highlighted and the targeted niche is identified. Secondly, the proposed decentralized control is discussed for the mitigation of

overvoltage problem. Last but not least, a hierarchical control is proposed for the mitigation of overloading problem.

2.1. Problem formulation

Let assume a line segment with an impedance of $R + jX$, which connects a sending end bus with a receiving end bus, as shown in [8]. Further considering a DRES which injects power (P_{inj}) to the receiving end bus, thus the relation between the sending end voltage (\bar{V}_S) and the receiving end voltage (\bar{V}_R) can be written as:

$$\bar{V}_R = \bar{V}_S - \bar{I}_R(R + jX) \tag{1}$$

The apparent power at the receiving end bus is $P_R + jQ_R$ and (1) can be expressed as:

$$\bar{V}_R = \bar{V}_S - \left(\frac{P_R - jQ_R}{\bar{V}_R^*} \right) (R + jX) \tag{2}$$

Assuming DRES operated in unity power factor mode i.e. ($Q_R = 0$) and it has been found in [12–14] that for the LV network consist of underground cables (X/R) < 1 thus (P_{RX}) << 1. In addition, considering \bar{V}_R as the reference voltage with zero angle, i.e. $\bar{V}_R = V_R \angle 0^\circ$. Thus, (2) can be approximated as:

$$V_R \simeq \bar{V}_S - \left(\frac{RP_R}{V_R} \right) \tag{3}$$

Herein, ($P_R = P_L - P_{inj}$), but it is known that the overvoltage is maximum under no load condition, i.e. $P_L = 0$. Thus, (3) can be simplified as:

$$V_R \simeq \bar{V}_S + \left(\frac{RP_{inj}}{V_R} \right) \tag{4}$$

2.2. Decentralized control for overvoltage mitigation

It can be inferred from (4) that as DRES penetration increases (P_{inj}), it may lead to overvoltage consequently it may limit the further penetration of DRES in LV network. In practice, due to load demand, the overvoltage problem may occur for few hours of some days in a year. That is why, in order to mitigate the overvoltage problem, a control is required to limit P_{inj} during the critical time.

Herein, the decentralized control a control that can self-heal the overvoltage problem by using local measurements. Although currently the commercially available controllable inverters (CIs) are equipped with a feature to limit its output power (P_{inj}) as expressed in (5), they are not equipped with any self-healing control like P–V droop control. So, power-limiting set point (P_{set}) can be used by any external control to mitigate the overvoltage problem.

$$P_{inj} = \begin{cases} 0 & \forall P_{set} & | V_g \notin [V_{max} \ V_{min}] \\ P_{MPP} & \forall P_{set} > P_{MPP} & | V_g \in [V_{max} \ V_{min}] \\ P_{set} & \forall P_{set} \leq P_{MPP} & | V_g \in [V_{max} \ V_{min}] \end{cases} \tag{5}$$

where P_{MPP} is instantaneous power at maximum power point, V_g is voltage at the point of connection, $[V_{min} \ V_{max}] = [0.9 \ 1.1]$ pu is an acceptable range for operation as per EN 50160 [36].

Although several researchers have already proposed embedded solutions using P–V droop control to mitigate overvoltage problem [18,37,33,34], CIs are manufactured to maximize customers benefit by injecting maximum power. Since P–V droop control does not add much value to customer benefit yet, the manufactures of CIs do not prefer to embed these solutions. However, it adds value to distribution network operator (DNO) because it helps to defer the investment in their networks. In addition, due to the closed system design, it is not easy to embed any other control in most of the available CIs. Therefore, an emulated droop control is proposed

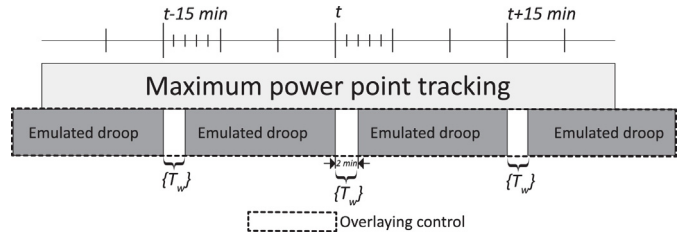


Fig. 1. The overlaying control and MPPT control runs in parallel.

in this work that can be easily implemented in real-life by using commercially available CIs without any design change.

2.2.1. Emulating the droop control

As in [18,33,34], the conventional embedded P–V droop control reduces the output power of DRES as the voltage at the point of connection of the inverter (V_g) crosses a threshold voltage value (V_c). The reduced output power (P_{droop}) can be expressed as:

$$P_{droop} = \begin{cases} P_{MPP}, & V_{min} < V_g \leq V_c \\ P_{MPP} - P_{MPP} \frac{V_g - V_c}{V_{max} - V_c}, & V_c < V_g < V_{max} \\ 0, & \text{otherwise} \end{cases} \tag{6}$$

From (6), it can be implied that if the conventional P–V droop control is embedded in CI, then the control cannot keep track of the new maximum power point ($P_{MPP}(t+1)$) over a change in output power $P_{droop}(t+1)$ from $P_{MPP}(t)$. Similarly, if the P–V droop control is not embedded in CI which is always the case, then the P–V droop control has to determine new $P_{MPP}(t+1)$ over a change in output power $P_{set}(t+1)$ from $P_{MPP}(t)$. Therefore, (6) cannot be used to emulate P–V droop control in CIs. Thus, for this situation, (6) is modified as:

$$P_{set} = \begin{cases} P_{MPP}, & V_{min} < V_g \leq V_c \\ P'_{MPP} - P'_{MPP} \frac{V_g - V_c}{V_{max} - V_c}, & V_c < V_g < V_{max} \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

where P'_{MPP} referred as virtual maximum power point is a new parameter which can be used for determining P_{set} . In this paper, an algorithm is proposed to calculate virtual maximum power point (P'_{MPP}), which is shown in Figs. 1 and 2. Thereby, P–V droop control can be emulated in CIs by using (7). Here, P'_{MPP} is not an actual P_{MPP} . Moreover, in order to avoid any hardware-related changes in CIs, as shown in Fig. 1, the proposed overlaying control is modelled such that it runs in parallel with the original maximum power point tracking (MPPT) algorithm of CIs. It is due to the fact that the MPPT algorithm of CI follows P_{set} , as expressed in (5). The algorithm to identify P'_{MPP} and to calculate P_{set} is shown in Fig. 2. The input data to the algorithm are the output power of the inverter (P_{inj}), voltage at the point of connection of the inverter (V_g) and time stamp (t) of the measurements. In addition, it is clearly shown in Fig. 1 that the emulated droop control repeats itself and thus updates (P'_{MPP}) after every 15 min.

Fig. 1 shows that once the emulated droop is activated, it should remain under this emulated droop control for some time. So, it can be observed from grey-coloured layer in Fig. 1, the approach is continuously emulating the droop control together with maximum power point tracking algorithm. However, during this grey window, the overlaying control misses the track of actual P_{MPP} . Therefore, to recapture the actual P_{MPP} , the P_{set} is assigned to its maximum value of inverter’s rated power (P_{rat}). In other words, the emulated droop control should be switched off for a time period during which inverter would be able to back track its actual P_{MPP} .

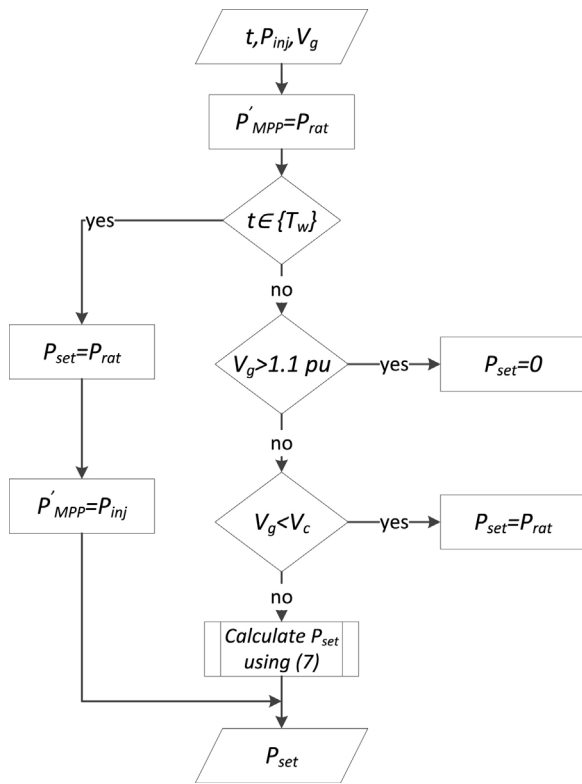


Fig. 2. The algorithm of overlaying control.

Therefore, a two min window (T_w) which can be observed clearly from Fig. 1 is chosen to allow inverter to recapture the actual maximum power point (P_{MPP}). As shown in Fig. 2, in the two minutes window (T_w), the output power is equal to the maximum power point, which is recorded as P_{MPP} . The given size of window has been selected after performing several experiments, which is discussed in Appendix A.1.

2.3. Hierarchical control for overloading mitigation

A multi-agents based hierarchical architecture can be used to mitigate the transformer overloading [38]. The hierarchical architecture that can be used for implementing the unified overvoltage mitigation and overloading mitigation is developed by authors and presented in [39]. In multi-agents based hierarchical architecture, there is an upstream agent to whom downstream agents are connected. In this scenario, a downstream agent can be equipped with emulated droop control, thus it will be able to mitigate overvoltage problem using local operating environment. On the other hand, upstream agent can communicate to its downstream agents for activation of droop control during any critical situation. So, in case, if upstream agents observe transformer overloading, it asks downstream agents to perform required control which might result in mitigation of overloading.

That is why, the algorithm proposed in the paper can be extended for the mitigation of transformer overloading just by having an upstream agent that is capable to coordinate with downstream agents. Although this paper suggests the solution for congestion management, the integrating mechanism between the agents is out of the scope of this paper. Furthermore, the proposed solution i.e. the emulation of the droop control leads to unequal power injection among the inverters. Therefore, a solution for unequal power injection was developed in [40], which can be realized by using the hierarchical architecture. Moreover, as a proof,

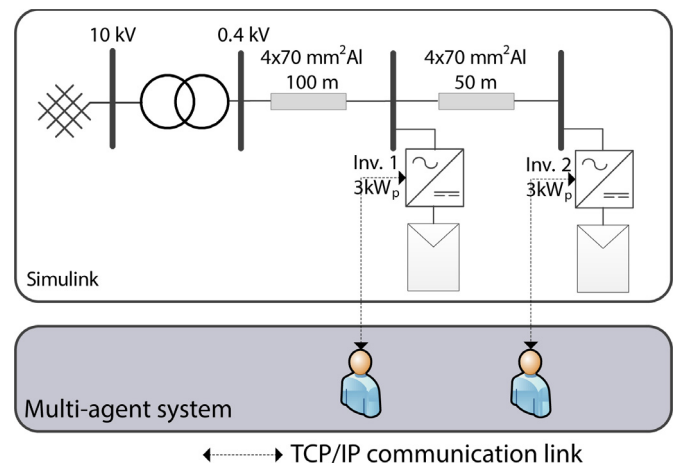


Fig. 3. The topology of the simulated network.

the communication among the agents in the developed hierarchical architecture is shown in Fig. A2.

3. Simulation analysis

A co-simulation model is developed to verify the overlaying control numerically. The co-simulation model consists of a LV feeder developed by using Simulink/SimPowerSystems and cyber-physical systems (or multi-agent system) developed by using Java Agent Development Framework (JADE), as shown in Fig. 3. In this section, the proposed overlaying control is verified numerically by using a co-simulation model that includes: TCP/IP-based communication link, the network parameters as provided in Table. 1 and two CIs. It can be recalled that the CIs consist the control feature, as expressed in (5).

The proposed overlaying control is programmed inside agents or cyber-physical systems in JADE environment. On the other hand, the LV feeder is modelled in Simulink environment. The two environments are connected via TCP/IP protocol. On contrary, the actual CIs used in experiment use MQTT protocol for communication. That is why, the communication delay of 3 s (typical delay value when MQTT is used) is considered in the co-simulation model [41–43]. Moreover, as per the name plate details of the available CIs, the measurement resolution of the inverter is modelled as 5 s, which means CIs can receive a new power-limiting set point after every 5 s. Lastly, the simulation is conducted for 24 h and zero load condition are assumed. A sunny day irradiation profile presented in [8] is used for the simulation.

3.1. Results

Herein, two different cases are simulated by using the co-simulation model. In first case, no overvoltage mitigation control is used and the corresponding results are shown in Fig. 4 by dashed lines. In second case, the proposed overlaying control is realized and the corresponding results are presented in Fig. 4 by solid lines.

Table 1
Data of the simulated low voltage network.

Devices	Value
Feeder length	150 m
Distance between two inverters	50 m
Conductor	70 mm ² Al
MV/LV transformer size	250 kVA
Inverter size	3 kVA
Irradiation profile	Sunny day

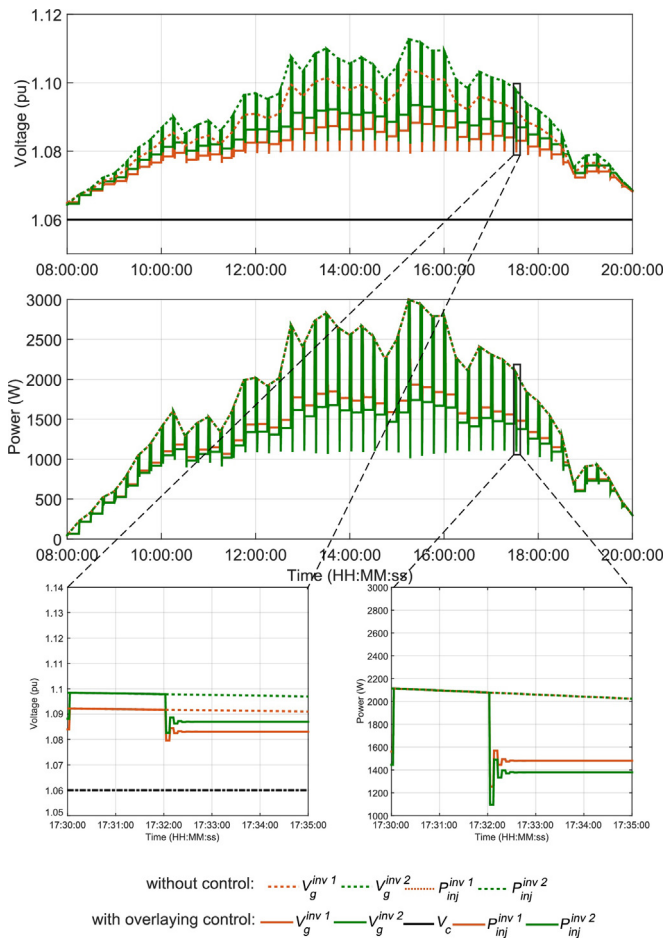


Fig. 4. Overlying control mitigating the voltage rise.

Though the simulation was conducted for 24 h, for the sake of explanation, the simulation results are shown in the windows of 8 hour and 5 min in Fig. 4. Next, it can be recalled, the overlying control is programmed to mitigate the voltage rise once the voltage at the point of connection of inverter exceeds threshold voltage V_c i.e. 1.06 pu. As shown in Fig. 4, the voltages at the point of connection of inverters ($V_g^{inv i}$) varies as the output power of the inverters $P_{inj}^{inv i}$ are varied. At 17:32:00, the agents of inv 1 and inv 2 receive voltage measurements and power measurements from the corresponding inverters. At 17:32:00, since $V_g^{inv 1}$ and $V_g^{inv 2}$ are higher than V_c i.e. 1.06 pu, the output power of these inverters are limited by the agents consequently $P_{inj}^{inv i}$ are reduced and $V_g^{inv i}$ are mitigated.

Fig. 4 also shows when the simulation is conducted without any overvoltage mitigation control, from 12:30:00 upto 17:15:00, the voltage at the point of connection of inv 1 ($V_g^{inv 1}$) exceeded 1.1 pu thus violated overvoltage limit. Similarly, inv 2 also suffered from overvoltage for the durations 13:15:00–13:30:00 and 15:00:00–16:00:00. In contrast, when the simulation is conducted with the overlying control, the overvoltage problem is mitigated

considerably. To quantify overvoltage mitigation, VVI index as shown in (8) is used and the results are presented in Table 2.

$$VVI = \frac{t_{ov}}{T} \tag{8}$$

where VVI is Voltage Violation Index; t_{ov} is the duration of overvoltage; T is the total duration.

Table 2 shows that the overlying control mitigated the overvoltage problem however it could not solve the overvoltage problem completely. The overlying control lead to the increased energy generation than the case without any control. It can also be noted that the energy generation did not include the PV power generation when voltage at the point of connection of inverter is higher than 1.1 pu. Furthermore, it can be observed from Fig. 4 that both the inverters reached the steady state output power simultaneously and the proposed overlying control leads to a unequal power curtailment between inv 1 and inv 2.

4. Laboratory verification

The proposed overlying control is further tested in a laboratory setup, by using the same network configuration, as shown in Fig. 3. First, instead of the distribution transformer, a voltage source (45 kVA) is connected at the beginning of the feeder. Second, to emulate the DC output of PV panels, a PV simulator is used. Third, in order to avoid the interaction between the voltage control loop of the voltage source and the voltage control loop of CIs, a resistive load is connected at the beginning of the feeder. Fourth, commercially available CIs referred inv 1 and inv 2 are connected to the feeder, as shown in Fig. 5. Fifth, each CI is embedded with MQTT clients in order to communicate with the agent, referred as cyber-physical system, as shown in Fig. 5. The cyber-physical system or agent implements the proposed overlying control.

The paper tries to verify the overlying control in three different cases: (i) testing the stability of overlying control under constant irradiation, and a new power-limiting set point after every 5 s; (ii) testing the stability of overlying control under a variable irradiation profile, and a new power-limiting set point after every 30 sec; (iii) testing the scalability of overlying control using more than one inverter under a constant irradiation.

4.1. Case 1: Testing under constant irradiation

The network configuration of the experiment is shown in Fig. 5, which is similar to the simulated network, but, in this case, only inv 1 is connected to the feeder. Herein, two set of experiments are conducted:

Experiment 1a: A new power-limiting set points (P_{set}) after every 5 s and a constant irradiation of 3000 W.

Experiment 1b: A new power-limiting set points (P_{set}) after every 1 min and a constant irradiation of 2400 W.

To compare the result of numerical simulation ($P_{inj}^{inv 1, sim}$ and $P_{set}^{inv 1, sim}$) against the laboratory experiment ($P_{inj}^{inv 1}$ and $P_{set}^{inv 1}$), the result of numerical simulation is presented in a 15 min window that is shown in Fig. 6. Both in experiment 1a and in the simulation, the overlying control mitigates overvoltage

Table 2
The impact of overlying control.

	Voltage Violation Index (%)		Energy generation (kWh)		
	Inv 1	Inv 2	Inv 1	Inv 2	Total
Without control	5.70	19.03	17.29	9.48	26.78
With overlying control	0.84	2.53	15.28	13.42	28.70

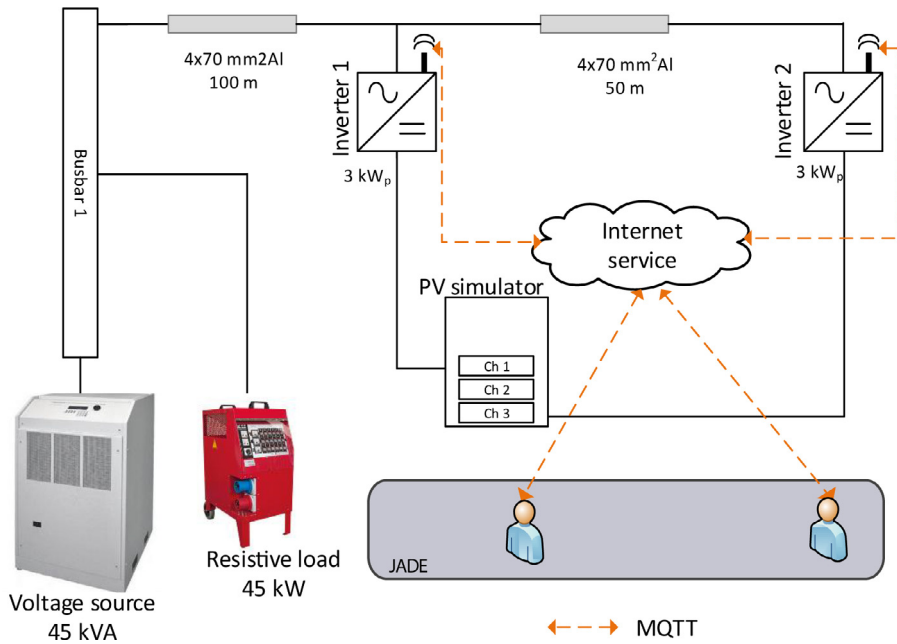


Fig. 5. Laboratory testbed for verifying the overlaying control.

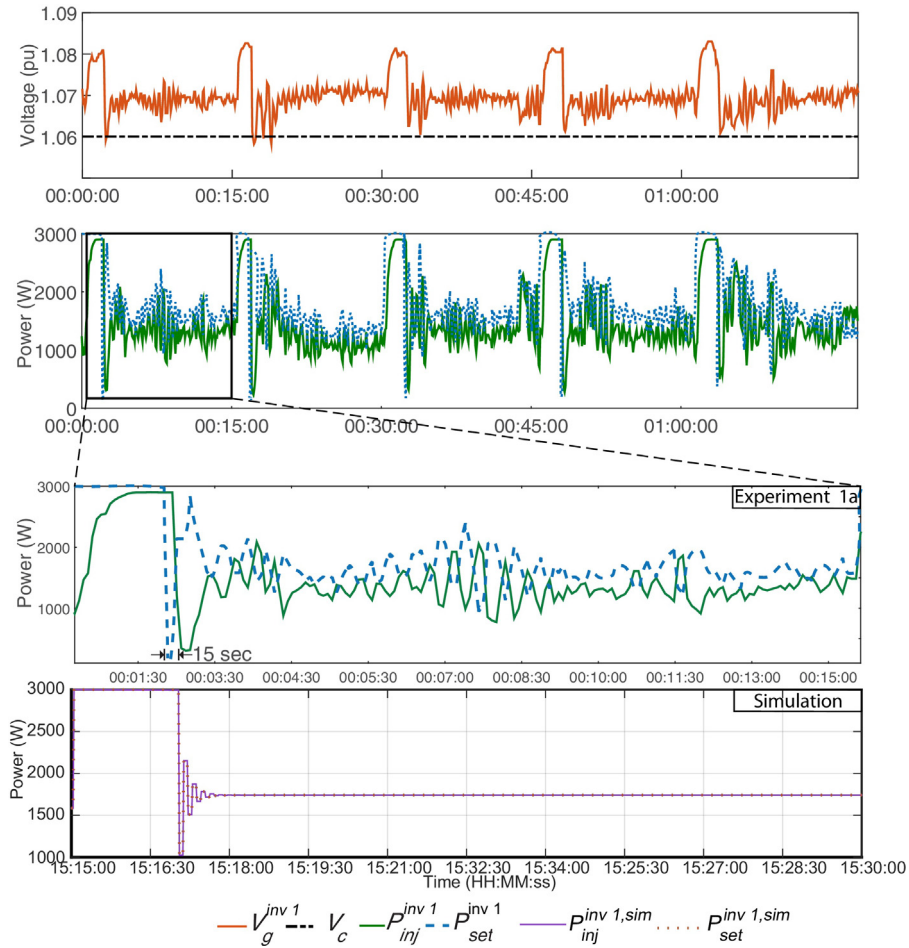


Fig. 6. The response of inverter for P_{set} after every 5 s.

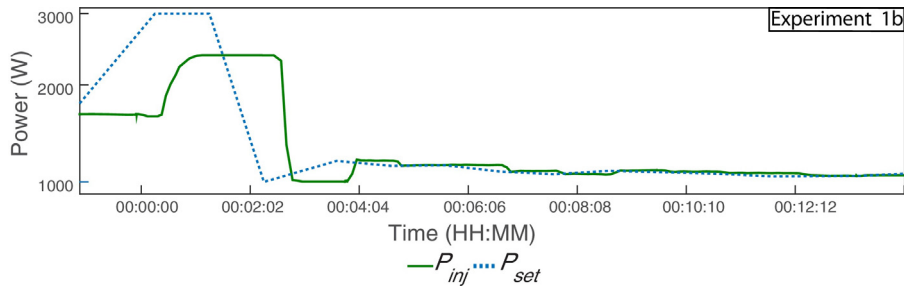


Fig. 7. The response of inverter for P_{set} after every 1 min.

problem by sending new P_{set} after every 5 s. However, though the simulation results shows the stable output power for inv 1 ($P_{inj}^{inv1, sim}$), experiment 1a result shows that the output power of inv 1 (P_{inj}^{inv1}) is not stable and thus the voltage (V_g^{inv1}) is not stable as well, which is shown in Fig. 6. Because, as shown in Fig. 6, the output power (P_{inj}^{inv1}) required almost 15 s to follow the new P_{set}^{inv1} whereas inverter 1 sent new P_{set} after every 5 s. Therefore, it created the overshoots in P_{set} and thus it led to instability in P_{inj}^{inv1} . Next, the same experiment is repeated for new P_{set} after every 1 min and the result is shown in Fig. 7. It can be observed that inverter 1 required more than 5 min to reach a steady output power in experiment 1b. A comparison of these two results reveals that the short time interval (5 s) between new power-limiting set points lead to instability. On the other hand, longer time interval (1 min) between new power-limiting set points lead to increased stabilization time.

In order to identify an optimal time interval for new power-limiting set points (P_{set}), more experiments are conducted for various change in P_{set} and the results are shown in Fig. A1. However, in real-life, the CIs sends the measurement after every 5 s. As a remedy, the agent are programmed to send P_{set} after every 30 s. The agent calculate RMS value of measurements that are arrived in last 30 s. Next, it calculates P_{set} by using (7) and send it to the inverter.

After incorporating the optimal time interval i.e. 30 s, it was found that the voltage rise problem can be mitigated experimentally without any instability problem. A better inverter design can lead to a smaller response time and thus faster stabilization of the output power, which is not the scope of this research.

4.2. Case 2: Testing under variable irradiation

The optimal interval between new power-limiting set points is identified as 30 s, which is applied in case 2. In this experiment a variable irradiation profile (P_{MPP}), as shown in Fig. 8, was used to test the overlaying control. It is important to explain that the variable irradiation is a derivation of a real-sunny day irradiation profile, in which, the rate of change of the variable irradiation is 16 times faster than the rate of change of the real-sunny day irradiation. Moreover, in this experiment, the performance of the proposed overlaying control is verified under both positive and negative gradients of irradiation.

It can be recalled, the commercially available inverter loses P_{MPP} when it curtails the output power therefore the virtual maximum power point (P_{MPP}') need to be identified. In this experiment, as shown in Fig. 2, the virtual maximum power point is recorded after every 15 min, which is shown in Fig. 8. By using the recorded P_{MPP}' and (7), the new power-limiting setpoints (P_{set}) was calculated. It can be observed from Fig. 8 that P_{MPP}' (purple line) is updated after every 15 min. At 00:02 and 00:17, the voltage at the point of connection of the inverter (V_g) was higher than V_c i.e. 1.06 pu. Therefore, new P_{set} are sent to the inverter and thus

the output power of the inverter is reduced consequently V_g is reduced. In contrast, the output power of the inverter (P_{inj}) is not reduced at 00:32. Because at 00:32, the voltage at the point of connection of the inverter (V_g) did not cross V_c i.e. 1.06 pu. Therefore it can be inferred that the overlaying control limits the output power only when the voltage crosses V_c , as shown in Fig. 2.

After 00:23, though P_{set} increases, P_{inj} continue to decrease, which is explained using (5). Furthermore, as claimed the response time of the inverter for a new P_{set} is not more than 30 s, which can be observed in Fig. 8 specifically at 00:17:42. Moreover, it can be noted that P_{MPP}' is updated after every 15 min, as shown in Fig. 2.

4.3. Scalability

The scalability of overlaying control is tested using two inverters, as shown in Fig. 5. The proposed overlaying control is embedded within two agents, as shown in Fig. 5 and V_c was set as 1.06 pu. In addition, both the inverters are operated under the same P_{MPP} thus the virtual power point (P_{MPP}') of both the inverters are equal. However, it can be inferred from Fig. 9 that the inverter at the end of the feeder (inv 2) curtailed more power than the inverter at the beginning of the feeder (inv 1). The same behaviour is observed in numerical simulation as well, which is shown in Fig. 4. Though the overlaying control mitigates the voltage rise problem, it leads to unequal power sharing among the inverters. Furthermore, unlike the simulation, the output power of inv 1, and inv 2 were reached the maximum output power on different time instances; the time difference is about 24 s. It was due to the fact that the MQTT clients of the inverters were connected with the internet service on different time. Consequently, the agents sent new power-limiting set points on different times.

The numerical simulation model did not include the granular level details of the real inverter such as the different connection time of the MQTT clients, and the varying communication delay.

5. Lessons learned

In the laboratory, ICT-related investigation revealed that new applications such as the one proposed in this paper, may require additional update in the original firmware of the inverter. Experiment showed that in case of a communication failure, controllable inverters (CI) continues to curtail power continuously until the communication failure is resolved. It could lead to unnecessary power curtailment for days. Therefore, authors made changes in the firmware of the inverter, which resets the power-limiting set point (P_{set}) to restarts. Therefore, in case of the communication failure, the inverter will not curtail power more than one day.

Another finding is that initially the internal clock of the inverter was not synchronized with its time server i.e. NIST timeserver. It was due to the additional security restrictions of the access point

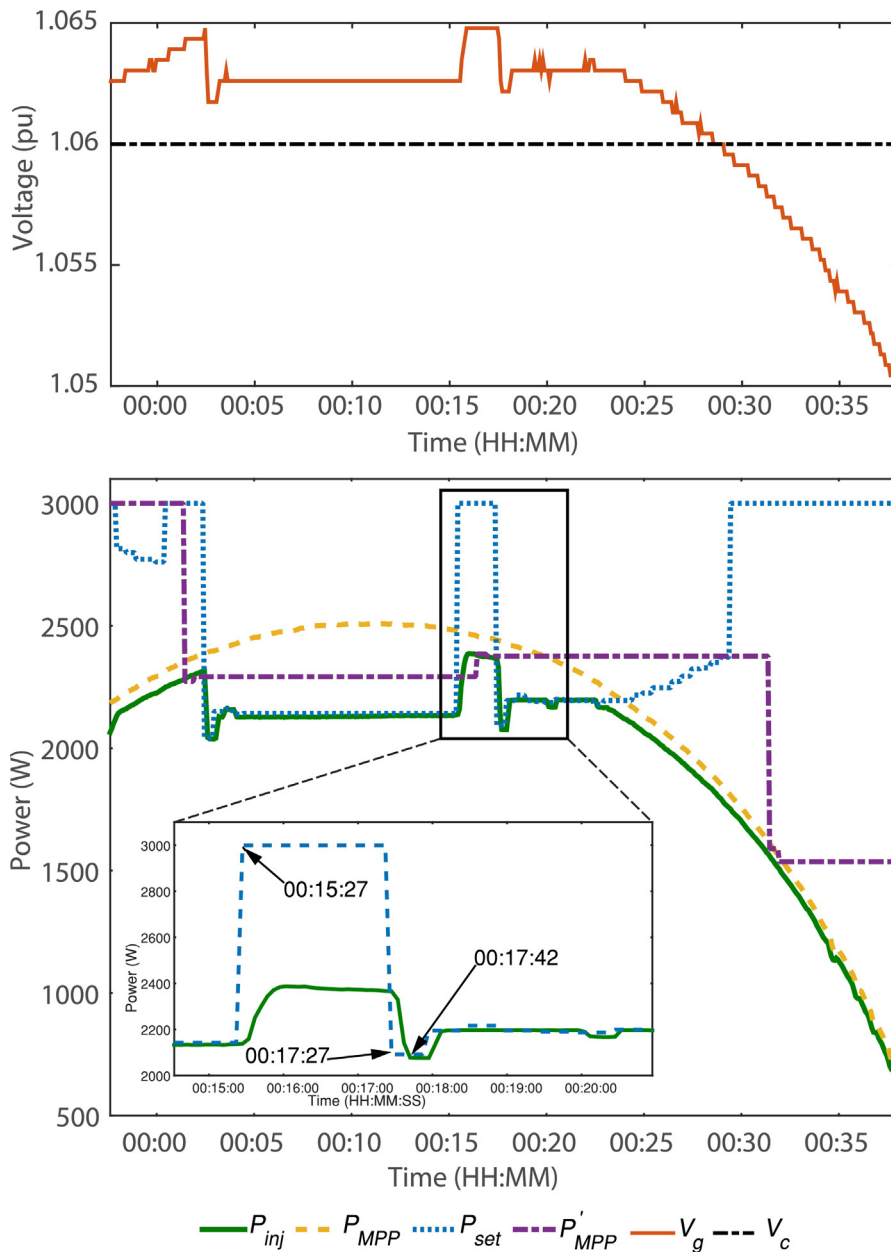


Fig. 8. Overlying control under variable irradiation.

to which inverters communication module was connected. Consequently, the measurements from an unsynchronized inverters generates wrong time stamp in the overlying control algorithm. Thus, it could lead to a situation, in which, the inverters that

are connected at the end of the feeder may trip. Turning to residential ICT infrastructure, the residential access point does not have the additional security restrictions. However, when the overlying control is implemented in a non-residential building, the inverters should be allowed to connect to all type of connections such as tcp, and udp in order to avoid the time synchronization problem.

6. Conclusion

The overlying control method is verified with laboratory experiments, which lay a foundation to roll out a large number of the smart inverters in real-life applications. A comprehensive control algorithm for commercially available inverters based on a hierarchical architecture of multi-agent system (MAS) is implemented. This scalable ICT paradigm can enrich the controllability of PV inverters to cope with multiple power quality issues in a flexible way by reprogramming the control algorithm thus

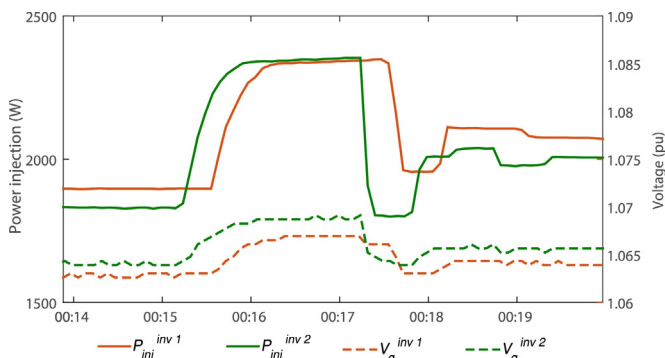


Fig. 9. The implementation of overlying control in two inverters.

prevents any new changes in the hardware or the firmware of CIs. The proposed overlaying control can be extended to solve additional power quality problem such as mitigating transformer overloading or unfair power curtailment. Moreover, the proposed control method is developed as a generic control by introducing the new parameter referred as virtual maximum power point. Therefore, the proposed overlaying control does not require any hardware-related changes either in solar PV inverter or in the existing communication infrastructure. As a proof of concept, laboratory experiments are conducted to test the overlaying control. In addition, the solutions for implementation challenges such as the optimal time interval between new power-limiting set points is identified and tested in the laboratory experiments. Thus, the proposed comprehensive control algorithm can serve as an open source application for distribution system operator to mitigate their power quality problems in real-time.

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Appendix A.

A.1. Identifying the hardware limitations of CI.

As shown in Fig. A1, a controllable inverter requires up to 30 s to follow a new power-limiting set point when it is limiting its output power ($-\Delta P_{set}$). Therefore, in order to avoid instability, the optimal time interval between new P_{set} is identified as 30 s.

On other hand, a controllable inverter requires maximum 1 min to follow the increase in the new power-limiting set point ($+\Delta P_{set}$), which is shown in Fig. A1. As explained in Section 2.2.1, P_{set} is recorded at the end of two min window. However, if P_{set} is recorded in one min window, the ramping P_{inj} will be recorded as P_{set} . Therefore, in order to avoid recording the ramping P_{inj} as P_{set} , two min window is used in this paper.

A.2. Identifying the hardware limitations of CI

Fig. A2 shows the communication among agents that are programmed with overlaying control. All inverter agents are informing the measurements to the aggregator agent (upstream agent) and thus the aggregator agent responds to the inverter agents with new power-limiting set point (P_{set}). The direction of arrows illustrates the bidirectional communication.

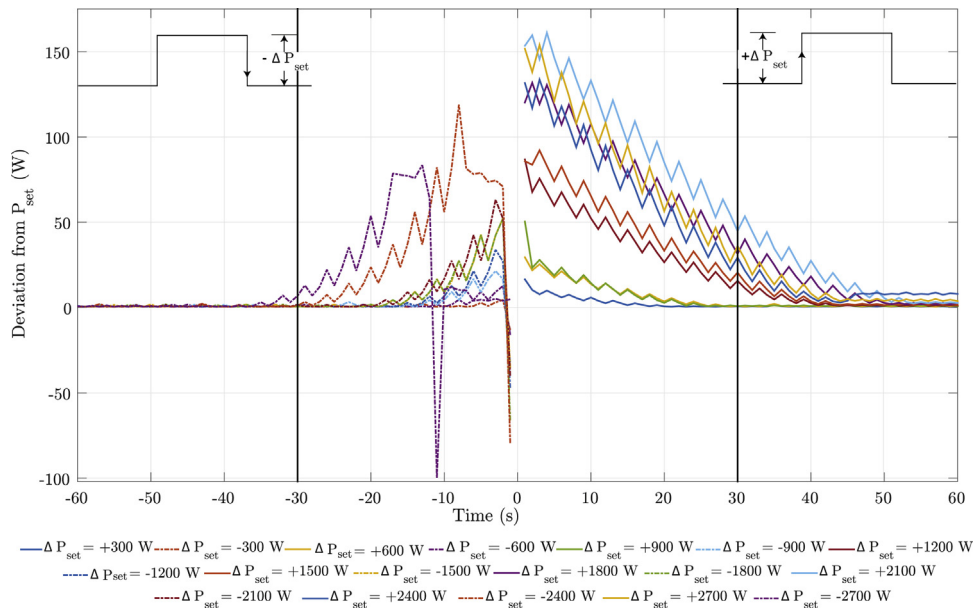


Fig. A1. Response time of the inverter for different ΔP_{set} .

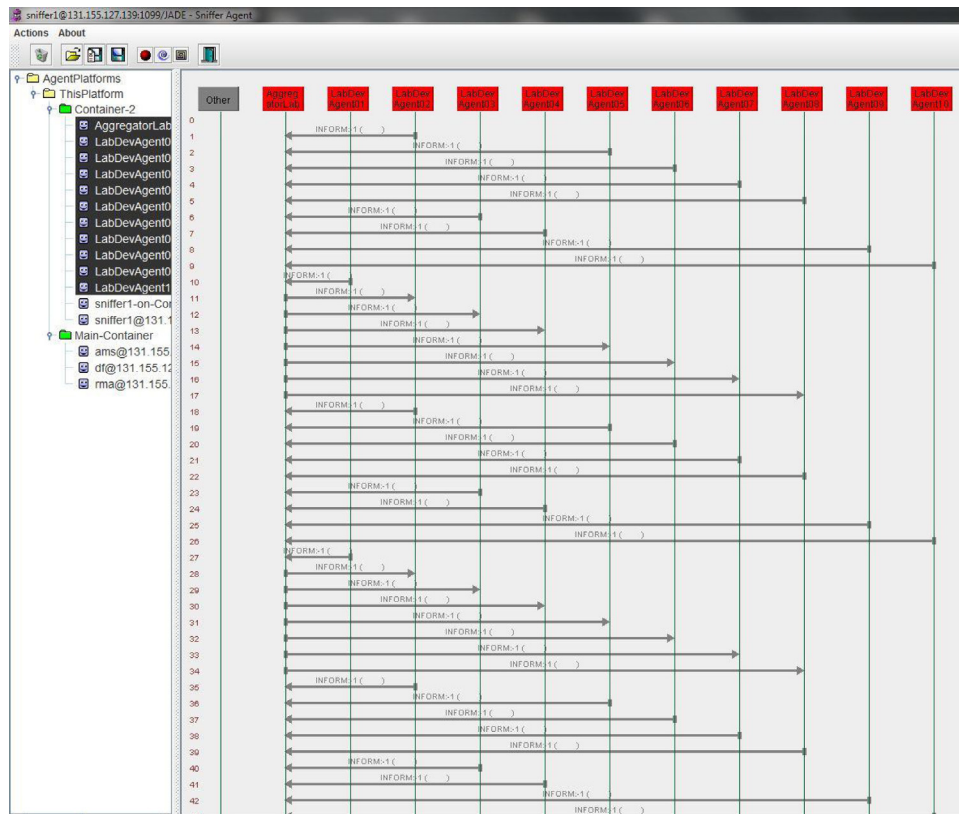


Fig. A2. Communication among the agents.

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