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Co-simulation of a Low-Voltage Utility Grid Controlled over IEC 61850 protocol

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Abstract—This paper presents a co-simulation model using MATLAB[®] toolboxes to illustrate an interaction between the communication system and the energy grid, coherent with the concept of smart grid that employs IEC 61850 communication standard. The MMS (Manufacturing Message Specification) protocol supported by IEC 61850, based on TCP/IP, is used for the vertical communication between the Supervisory and Data Acquisition (SCADA) system and Intelligent Electronic Devices (IEDs) embedding the local control of different parts of the smart grid. In this paper an IED supporting the power control of a photovoltaic (PV) plant connected to a low-voltage (LV) utility grid is considered. Communication system consisting of the transport layer and a router placed on the network layer is modeled as an event-driven system using SimEvents[®] toolbox and energy grid is modeled as a time-driven system using SimPowerSystems[®] toolbox. Co-simulation results are obtained by combining different communication scenarios and time-varying irradiance scenarios for the PV plant when this one is required to provide a certain power in response to a power reference received from SCADA over the communication network. The analysis aims at illustrating the impact that stochastic behavior and delays due to network communication have on the global system behavior.

Keywords—Co-simulation; delay; IEC 61850; Manufacturing Message Specification (MMS); TCP/IP; low-voltage (LV) grid

I. INTRODUCTION

The concept of smart grid at distribution level characterizes the information flow using latest communication technologies. A smart distribution grid is a modernized electrical grid (fully automated distribution system) that uses information and communication technology to improve reliability, security and efficiency of energy delivery [1]. So smart grids use complex commu-

nication networks in order to allow communication between the DERs (Distribution Energy Resources) to implement functions such as power monitoring, energy management and ADA functions (Advanced Distribution Automation). Smart grids are therefore highly automated cyber-physical systems. The concept of smart distribution grid has led to the development and implementation of new communication standards able to provide interoperability [2,3]. This increasing role of communication network in the operation and control of power system results in strong dependence of the global performance on the performance of communication [1]. As information flows through the communication network, it exhibits variable delays that can cause unstable behavior and some asynchronous events that can lead to loss of data. This highly automated power system is prone to vulnerabilities caused by interdependencies with communication and information systems [4].

Recent work has been reported in the literature [4, 5] on identifying and modeling these interdependencies. The implementation of widely used advanced protocols like IEC 61850 has been investigated in [3] and [6]. The detailed simulation of energy systems along with the communication architecture requires hybrid models, i.e., models including both continuous time-based and discrete-event-based simulation aspects. There are different domain-specific simulation tools that have been developed and described in the literature to simulate the dynamic system behavior for power systems in different frameworks, e.g., electrical systems, cyber-physical systems, control or stochastic environmental behavior [7]. A commonly tool available for such kind of analysis is Simulink[®] of MathWorks that can help in studying the behavior of models with hybrid dynamics. Other than this, developing co-simulation framework is also possible that allows the use of most appropriate expert tool for each domain. But in this case it has a disadvantage of making the different tools to work together efficiently [7]; e.g., time synchronization and data exchange of two fundamentally different simulators are major

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challenges [8]. Concerning the co-simulation framework, there are lot of approaches proposed in the literature that include using free and open-source available tools such as GridLAB-D and PSAT [7], or co-simulation tools, such as VPNET [8], combining INSPIRE & HLA [9]. The work proposed in this paper is using a more flexible approach for setting up a kind of co-simulation scenario in MATLAB[®], as compared to the one discussed in [7-11]. Fig.1 suggests the main idea of the implemented co-simulation architecture.

Use of IEC 61850 protocol over the energy grid results in hybrid global dynamics. This paper deals with the implementation of Manufacturing Message Specification (MMS) protocol supported by IEC 61850 communication protocol standard for controlling a photovoltaic (PV) plant connected to a low-voltage (LV) utility grid. Communication system consisting of the transport layer and a router placed on the network layer is modeled as an event-driven system using SimEvents[®] toolbox and energy grid is modeled as a time-driven system using SimPowerSystems[®] toolbox. Mechanisms related to acknowledgments and retransmissions specific to TCP/IP as well as management of router's queue length by means of Random Early Detection (RED) algorithm and congestion avoidance are implemented.

Co-simulation is performed to illustrate interaction between the communication system and the power system in terms of latencies affecting the global behavior of PV system. Fig. 1 depicts the general scenario of the studied interaction.

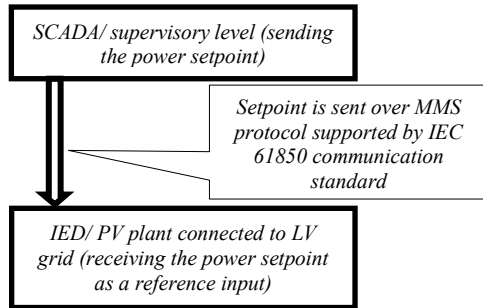


Fig 1. Overview of co-simulation approach implemented.

This paper is organized as follows. Section II discusses the IEC 61850-based communication system modelling. It is followed by Section III that describes LV utility grid modelling. In Sections IV and V, the coupled model and co-simulation results are presented, respectively, followed by conclusion of the work in Section VI, the final one.

II. IEC 61850-BASED COMMUNICATION SYSTEM MODELLING USING SIMEVENTS[®] / MATLAB[®]

A. IEC 61850-based Communication System

IEC 61850 standard characterizes a comprehensive structure for designing power utility automation system. This standard provides a data flow mechanism to exchange information among

the Intelligent Electronic Devices (IEDs) that embed the local control of different parts of smart grid.

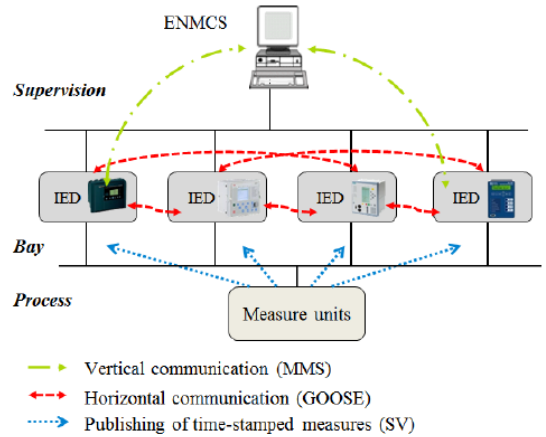


Fig 2. IEC 61850 communication architecture [12].

Fig. 2 shows the communication architecture of the standard, including three protocols: GOOSE (Generic Object Oriented Substation Event) messaging, MMS (Manufacturing Message Specification) and SV (Sampled Values) with two interface buses that support the data exchange.

B. Relation between IEC 61850 Standard and TCP/IP

IEC 61850 standard supports three protocols, namely GOOSE, SV and MMS to allow the data flow.

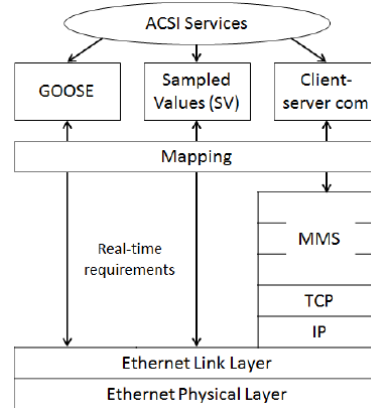


Fig 3. OSI mapping of IEC 61850 protocol.

MMS protocol supports MMS traffic that allows SCADA systems placed at supervisory level to access vertically all the IED objects. Its functioning is based on TCP/IP (layer 3). GOOSE traffic allows IEDs to access data horizontally. SV traffic carries the current and voltage samples used in discrete-time control. Out of the three mentioned protocols, MMS is the one that is based on TCP/IP layers and allows traditional supervision operations, i.e., read, write and report.

C. Transport Layer in TCP/IP

Transport layer is an end-to-end protocol that provides communication between two processes (application programs) running over different hosts. This layer sends data in segments. Transport layer supports two protocols: UDP (User Datagram Protocol) and TCP (Transmission Control Protocol). UDP is an unreliable connectionless protocol, whereas TCP is a connection-oriented protocol that provides reliable transport by establishing the connection between client and server before data transfer begins and releasing the connection after data transfer ends up. Hence TCP ensures error and flow control, as well as congestion control [13, 14].

D. TCP with RED (Random Early Detection) Router

It is difficult to build a router that does not drop packets even when it is overloaded with the incoming flow of packets. In order to allow the router to work properly, RED [15] algorithm is implemented, so as to keep a check on the moment of time the router should start discarding packets. Algorithm calculates the average queue length and, if it exceeds a pre-specified threshold, some packets are dropped on random basis. Main idea of the generalized RED algorithm is given below:

```

for each packet arrival
    calculate the average queue size (avg)
    if  $\min_{th} \leq avg < \max_{th}$ 
        calculate probability  $P_a$ 
        with probability  $P_a$ :
            mark the arriving packet
    else if  $\max_{th} \leq avg$ 
        mark the arriving packet
    
```

E. Error Control in TCP

TCP provides reliability using error control based on mechanism for detecting corrupted, lost, out-of-order and duplicated segments using simple tools like acknowledgment, retransmission and segment reassembly.

- Acknowledgment: TCP uses ACK signals to confirm the receipt of data segments.
- Retransmission: sender retransmits the data segment, in case segment is lost or delayed. This occurs in two conditions: when retransmission timer expires or when sender receives three duplicate ACKs.

Retransmission RTO: one retransmission time-out timer is maintained for all sent, but not acknowledged segments. When timer matures, earliest outstanding segment is retransmitted. The value of RTO is updated based on round trip time (RTT) of segments.

RTT: time needed for a segment to reach the destination and for an acknowledgement to be received.

- Segment reassembly: TCP guarantees data to be delivered to process in ordered sequence.

F. TCP Congestion Control

Congestion control refers to a mechanism where the load is kept below the capacity. Unlike UDP, TCP is able to control the network congestion by using congestion control algorithm that has four parts: Slow Start (SS), Congestion Avoidance (CA), Fast Retransmit and Recovery (FR). The algorithm for slow start and congestion avoidance is described below.

Slow start: Initialize
 $cwnd = 1$
 New ack received:
 $cwnd = cwnd + 1$
 In each RTT $cwnd = 2 * cwnd$

Congestion avoidance: Starts
 $cwnd \geq ssthresh$
 New ack received:
 $cwnd = cwnd + 1/cwnd$

In each RTT $cwnd = cwnd + 1$

SS starts by setting congestion window ($cwnd$) to one MSS (maximum segment size), size of $cwnd$ increases by one MSS each time an acknowledgment is received. This results in $cwnd$ increasing exponentially, because at each step it doubles. The congestion window $cwnd$ increases till it reaches $ssthresh$ (slow start threshold) tracked by the sender. When $cwnd$ reaches the

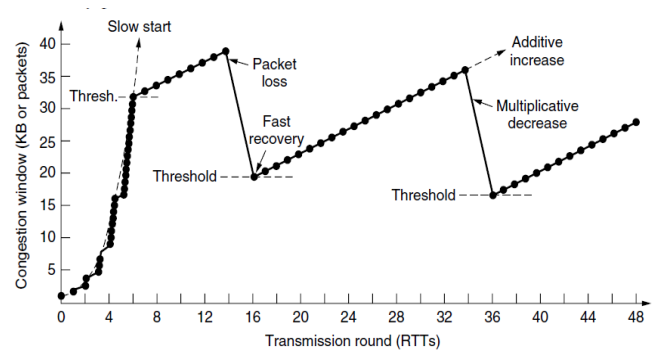


Fig 4. Congestion control algorithm [13].

threshold, slow start stops and CA starts operating, which causes the additive increase in $cwnd$. When congestion is detected, FR starts working and sender retransmits the segment. Then immediately fast recovery starts operating, which allows CA algorithm to take over the operation instead of allowing slow start. This operating mode is shown in Fig. 4.

G. TCP/IP-based Communication System Modelling in MATLAB[®]/SimEvents[®]

SimEvents[®] is a model-based simulation MATLAB[®] toolbox and is useful to model non-deterministic discrete-event systems, whose states changes upon the occurrence of discrete events. The toolbox is installed as a part of Simulink[®] library for MATLAB[®] and appears as a block library [16]. Discrete-event systems can

be constructed as entity processor units. Various blocks such as generators, queues and servers can be used to process the entities. This part of work includes an efficient implementation of TCP/IP-based communication system in SimEvents[®]. The TCP/IP protocol has been analyzed and its above described characteristic strategies have been implemented using SimEvents[®]. Basic simulation models reported in [17] have been used here.

III. LOW-VOLTAGE (LV) UTILITY GRID MODELLING USING SIMPOWERSYSTEMS[®]/MATLAB[®]

A. Photovoltaic (PV) Generation System

In this paper an IED supporting the power control of a PV plant connected to an LV utility grid is considered. A PV system is a power source designed to supply usable solar power by means of photovoltaic cells. Several single PV cells can be connected in series and parallel to form PV modules, and PV modules (or panels) can themselves be connected in series and parallel

in order to increase power.

A PV system includes then an arrangement of solar panels that absorb and convert sunlight into electricity. The PV panels produce DC current and are connected to the AC grid by means of inverters; here, a so-called back-to-back structure consisting of a DC/DC boost converter and DC/AC three-phase inverter is used (Fig. 5).

The PV plant consists of an n -by- m array of PV modules, where n is the number of parallel-connected strings, each with m number of series-connected cells. Here $n=7$ and $m=5$. The control block diagram of the grid-connected PV plant in Fig. 5 shows the two levels of control structure: an upper-level control containing the active power control and a low-level control in charge with DC/DC converter's voltage control. Notations in Fig. 5 are: P_{PVa}^* is the power reference, u_{ch}^* is the boost converter duty cycle reference, u_{inv}^* is inverter duty cycle reference, V_{DC} is DC-link voltage, I_{DC} is DC-link current and $i_{inv,dq}^*$ is inverter current references in dq frame.

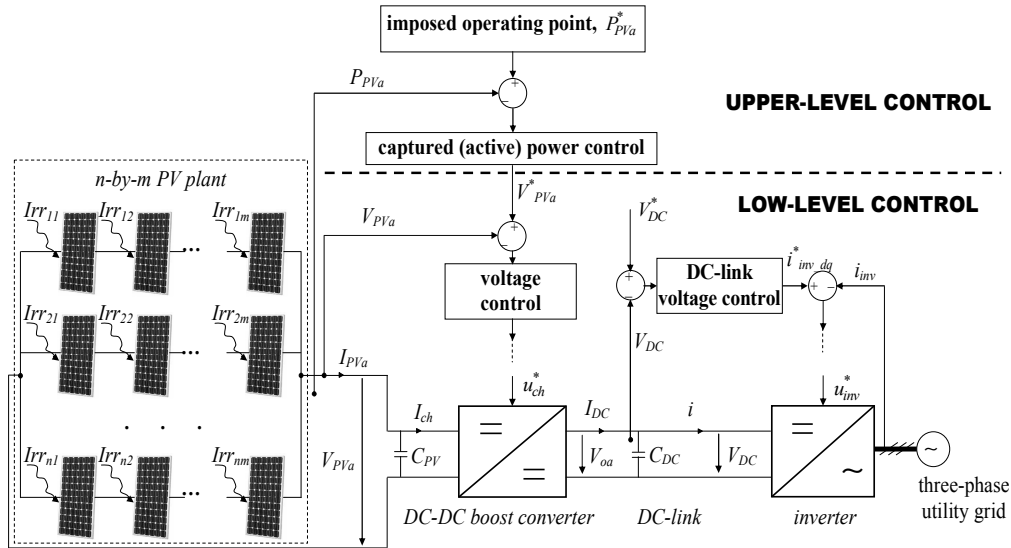


Fig 5. Grid-connected PV energy conversion system along with a two-level control structure [18].

B. Maximum Power Point Tracking (MPPT)

Grid-connected PV systems are usually required to provide a certain level of power whenever possible under the given irradiance conditions. When irradiance level is not sufficient to ensure the required power level, PV plant is controlled to provide the maximum power available. It is thus important to have an effective and appropriate MPPT algorithm for the PV system irrespective of irradiance variation. Lot of MPPT algorithms have been implemented in the literature [19-23], that include, among others, Perturb & Observe (P&O), Incremental Conductance (IC), Hill Climbing (HC).

In this work Hill Climbing algorithm has been used, namely

by varying the DC/DC boost converter duty cycle (D) by comparing the power at present and previous time. Thus, if incremental power $dP > 0$, then D is increased in order to make $dD > 0$; otherwise, if $dP < 0$, then D is reduced to make $dD < 0$. The current operating point is moved towards the maximum power one, characterized by $dP/dD = 0$.

C. Modified Maximum Power Point Tracking

The MPPT algorithm has been modified with the possibility of power control in order to get a certain power level, denoted by P_{PVa}^* . If the required power is larger than the maximum one that PV plant can deliver, then MPPT operation must be ensured.

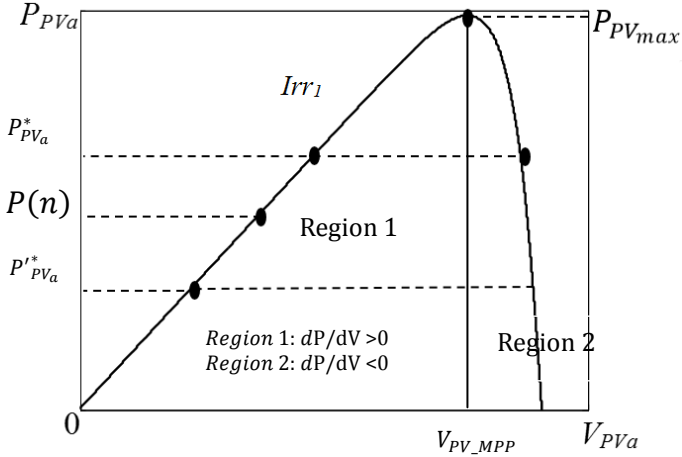


Fig. 6. Power-voltage curve of a PV plant for a given irradiance level Irr_1 .

In Fig. 6 the general power-voltage curve of a PV plant for a given irradiance level is shown. $P_{PV_a}^*$ is the power reference coming from an upper level; here the upper level is denoted as a dispatcher or supervisor, where the dispatcher is unaware of the maximum power that PV plant can provide at a given time. Modifications brought to the original MPPT algorithm are explained next. $P(n)$ and $P(n-1)$ denote measured PV power at current time and previous time steps, respectively.

CASE A : When $P(n) < P_{PV_a}^*$

CASE A.1: Voltage must increase as long as $P(n-1) < P(n)$ AND $P(n-1) < P_{PV_a}^*$.

CASE A.2: Voltage must decrease as long as $P(n-1) < P(n)$ AND $P(n-1) > P_{PV_a}^*$.

So in case A sign of voltage variation is same as in MPPT.

CASE B : When $P(n) > P_{PV_a}^*$

CASE B.1: Voltage must decrease as long as $P(n-1) > P(n)$ AND $P(n-1) > P_{PV_a}^*$.

CASE B.2: Voltage must increase as long as $P(n-1) > P(n)$ AND $P(n-1) < P_{PV_a}^*$.

So in case B sign of voltage variation must be reversed compared to the one for MPPT.

In conclusion, wherever the current operating point $P(n)$ is placed, if voltage variation is the one used for MPPT multiplied by $sign(P_{PV_a}^* - P(n))$, then power regulation at $P_{PV_a}^*$ is whenever irradiance level allows it. The modified MPPT algorithm flowchart is given in Fig. 7.

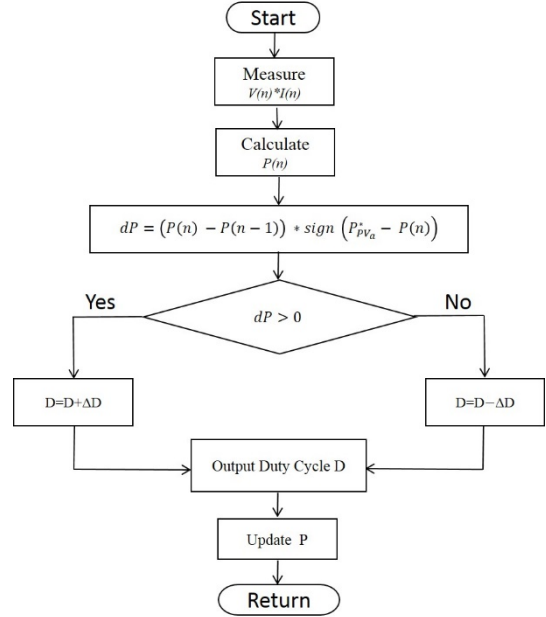


Fig. 7. Modified MPPT algorithm.

IV. CO-SIMULATION MODEL

It is considered that the PV plant included in the low-voltage distribution grid receives power setpoint, $P_{PV_a}^*$, from a dispatcher which belongs to a more complex and remotely located SCADA system. Therefore, reference signal $P_{PV_a}^*$ must be transmitted over a communication network. The protocol used to this end is the MMS from IEC 61850 operating over TCP/IP, used for communication between SCADA and the considered low-voltage distribution grid control system acting as an IED. Fig. 8 shows the coupling between the two models as a single Simulink® diagram, i.e., the event-driven communication model – detailed in Fig. 9 – and the time-driven model of the low-voltage distribution grid together with its control. An event-to-timed based signal conversion block was necessary to couple these two models.

V. CO-SIMULATION RESULTS

Simulation results shown next have been obtained under nominal conditions for the communication system. Thus, the network layer in the communication model is equipped with buffer space (queue) at the router that can store maximum 20 packets at a time. The router buffer has high capacity link at its input (as it can receive large number of packets without delay), but limited channel capacity output of 30000 bytes/second and this can lead to congestion in the network. The communication model has a constant line propagation delay of 0.1 seconds. This part of work is not concerned with the router behavior of distributing packets along the different paths, but instead with the router behavior in case of congestion, as that affects the delay times of the packets travelling through it. The delay experienced on the end-to-end path in the network can be decomposed into a deterministic (e.g., propagation) and a stochastic (e.g., queuing)

part. The deterministic delay is easy to estimate or evaluate, as it depends on factors such as packetization delay, propagation delay and service delay. The queuing delay is difficult to estimate as it depends on the congestion in the network. In order to keep a check on the queuing delay, the network load must be under control. In the upcoming simulation results we examine the effect of increasing load in the network on the delay experienced by the packets travelling through the router. One more parameter included in the communication model, i.e., the service time – equal to packet length divided by the channel capacity – has been calculated. In real world, power reference is a constant, at most it could happen that it varies step-wise, so we have provided a step-wise power reference signal to the system.

This input is first fed to the communication model, and the received power reference is fed to the power system. Setting the irradiance profile (ramp-up down) with peak value of 1000 W/m^2 , results in Fig. 10 show that power injected into the grid is following the profile of input irradiance. The power reference is set up as 8 kW. The first two figures show the effect of the modified MPPT algorithm: as long as the irradiance level is sufficient for the PV plant to provide the required power, the power at the utility grid is around the required one, i.e., 8 kW (except for the losses in the converters and transformers). If the irradiance level decreases so that P_{PVa} has reduced below the reference P_{PVa}^* , this means that the PV plant is not able to provide

the required power any longer. At that moment MPPT algorithm starts operating.

Queuing delay depends on the traffic load along the path and hence varies stochastically over the time. So as to measure this point-to-point delay experienced by the data traversing through the whole system, start and read timer blocks have been introduced as they jointly perform the timing computation. These timers compute the time each entity takes between arriving at the Emitter Transport level and departing from the Receiver Transport level. Fig. 10 is reporting the comparison between the sent power reference and the received power reference which feeds the control system of the grid-connected PV array under the nominal condition (router buffer: 20 packets, line delay: 0.1 s, channel capacity: 30000 bytes/second). The delay experienced in the received reference power sent further to the system shows a linear increase due to the fact that queue has become full of packets and as they are moving towards the head of the buffer router, they are adding up the delay (queuing delay). Because of this delay, power reference received by the PV plant control system is delayed. The last non delayed sample value is fed as reference – due to use of a zero-order hold element – as the two superposed plots show. This event is a short-time perturbation in the communication between the SCADA system and the PV plant control.

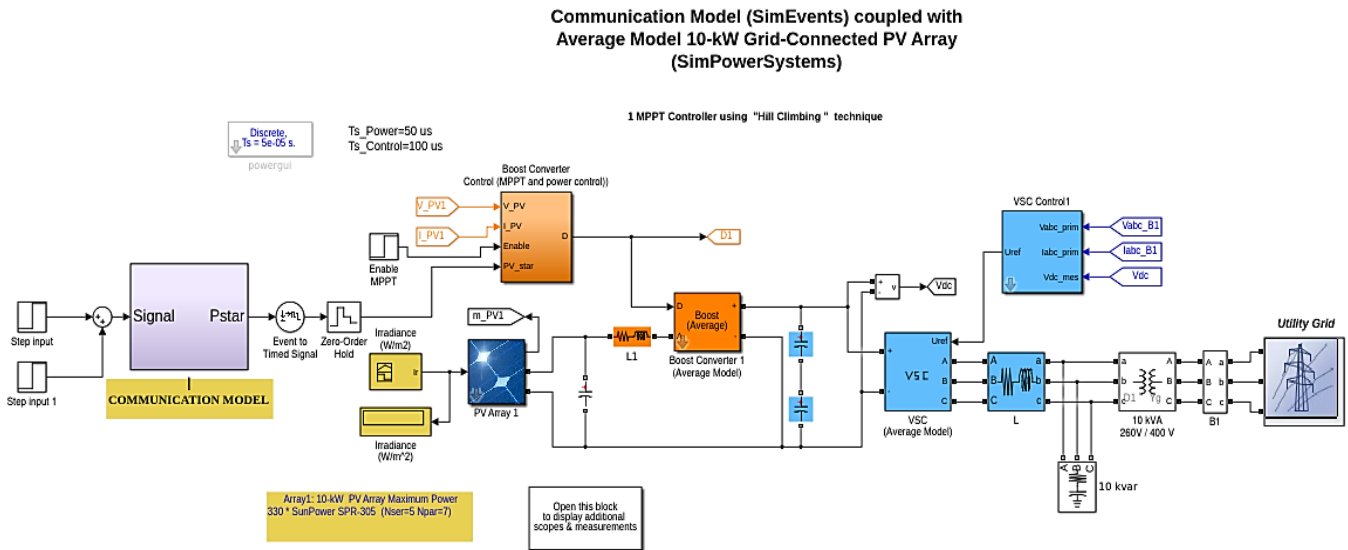


Fig 8. Communication model coupled with the model of a 10-kW grid connected PV array.

One more scenario has been examined that shows the effect of adding a perturbation in the system. A perturbation has been introduced as an extra data flow. After adding this perturbation the load on the network layer will increase and this will make queue more burdened with the incoming data. Hence queue will drop more packets as compared to the previous case. So, as to manage the dropping of packets, if space in router buffer will be increased, then this will cause delay to increase more.

So a better solution is to increase the channel capacity (in this case it has been increased to 60000 bytes/second), as this will cause the service time for the packets to be less than the previous case. Hence, channel would be able to output the data more quickly and network congestion would be avoided. This can be validated from the result in Fig. 11 that shows shorter delay between the sent power reference and the received power reference.

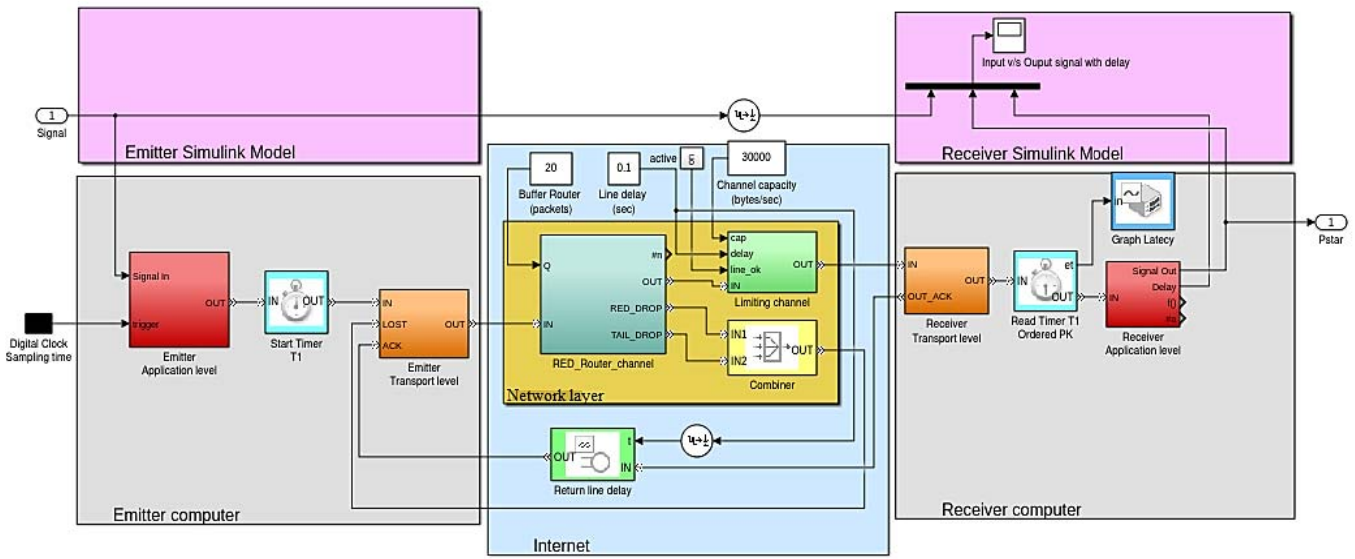


Fig 9. Communication model included in the coupled model.

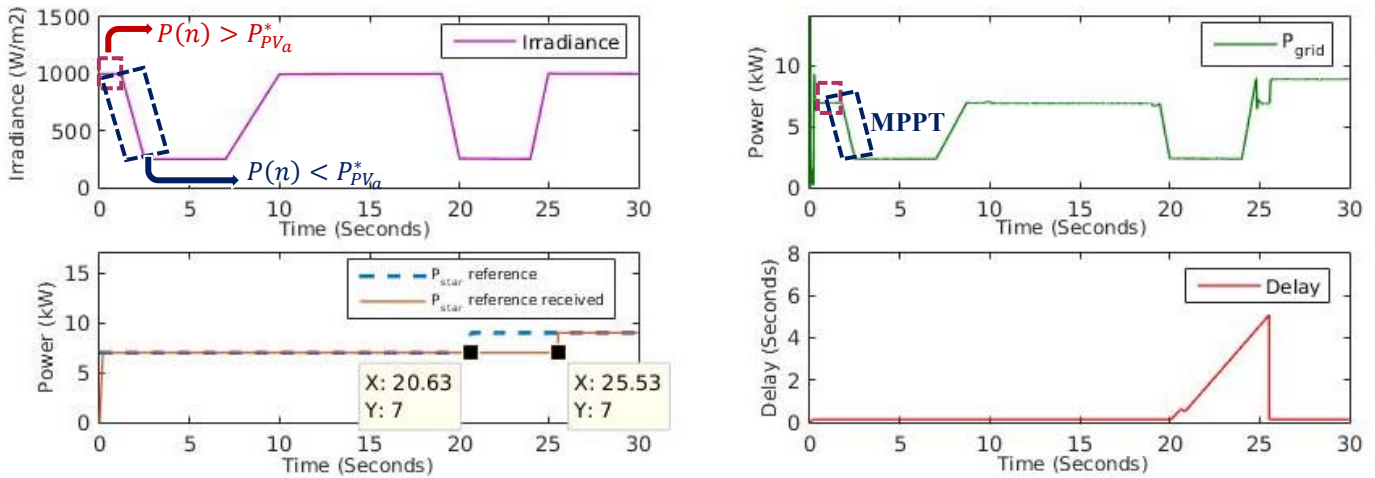


Fig 10. Co-simulation results in the nominal case.

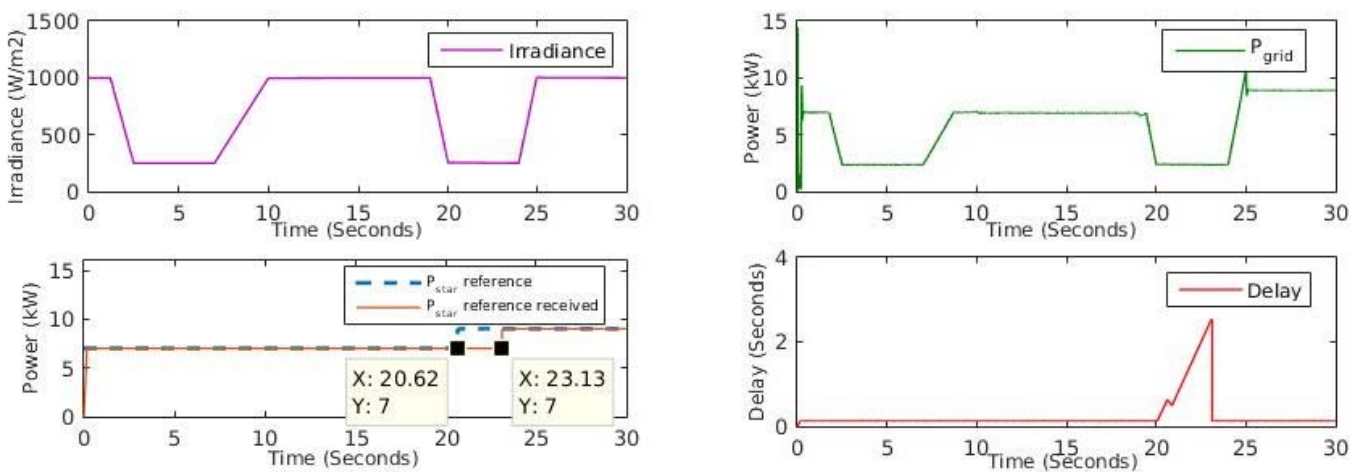


Fig 11. Co-simulation result when perturbation is added in input and channel capacity is increased.

VI. CONCLUSION

This paper investigates how the interaction between the communication system and the energy grid affects the global behavior of a smart grid, as the communication parameters affect the data transmission in the power system. The communication model based on TCP/IP protocol (MMS from IEC 61850) has been incorporated for establishing the vertical communication between the SCADA system and IEDs, where the IED considered here is the local control system of a PV array connected to an LV grid. The MATLAB[®] co-simulation results have shown that changing the parameters such as input to the communication system, router buffer, and channel capacity changes the data flow in the power system. It can be concluded that if the input data flow is increased, the router buffer can help in reducing the data loss but on the other hand it will lead to increase in delay. A better idea is to increase the channel capacity wherever possible, so as to avoid the network congestion.

Future work will aim at enriching the proposed co-simulation model and using it to derive an as general as possible formal model suitable for a large class of smart grids.

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