Poster Abstract: An OMNeT++ Model of the Control System of large-scale Concentrator Photovoltaic Power Plants

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ABSTRACT

The communication system of a large-scale concentrator photovoltaic power plant is very challenging. Manufacturers are building power plants having thousands of sun tracking systems equipped with communication and distributed over a wide area. Research is necessary to build a scalable communication system enabling modern control strategies. This poster abstract describes the ongoing work on the development of a simulation model of such power plants in OMNeT++. The model uses the INET Framework to build a communication network based on Ethernet. First results and problems of timing and data transmission experiments are outlined. The model enables research on new communication and control approaches to improve functionality and efficiency of power plants based on concentrator photovoltaic technology.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design; C.2.4 [**Computer-Communication Networks**]: Distributed Systems; H.4.3 [**Information Systems Applications**]: Communications Applications; I.6.5 [**Simulation and Modeling**]: Model Development

General Terms

Model, Topology, Ethernet, Power Plant, Industrial Applications

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1. INTRODUCTION

Concentrator Photovoltaic (CPV) systems promise to be one of the most cost efficient methods for generating electricity from sunlight in regions of high Direct Normal Irradiance (DNI). CPV technology requires direct irradiation due to optical lenses which concentrate the sunlight on high efficient multijunction solar cells. Modern CPV modules achieve an efficiency of more than 33% [1] while flat Photovoltaic (PV) modules only reach module efficiencies around 20 % [10]. The system technology of CPV power plants is significantly more complex as CPV systems need to track sunlight very accurately. The mismatch between ideal and real position should be less than 0.1 degrees that the optical lenses focus all sunlight on the cells [4]. Distributed control units located at every sun tracker calculate the signals for mechanical actors and measure the actual state of the system. The devices are equipped with communication interfaces to receive control signals from the control center of the plant or to deliver measurement values. As the sizes of such power plants increase, and with upcoming new requirements on the control system, the communication infrastructure of such power plants becomes challenging.

Communication is also necessary for basic operation. For instance, if the wind exceeds a given threshold all sun trackers need to move into a safe position to prevent mechanical damage. Not every sun tracker is equipped with meteorological sensors. This signal is to be sent over a communication medium. Especially large-scale CPV installations need to have an enhanced communication infrastructure allowing the operator to monitor and control the energy production of the complete power plant and every single sun tracker. Beyond that basic operation, communication is necessary to implement sophisticated control strategies for optimized operation, monitoring and maintenance [2]. One interesting use-case comes up when CPV power plants are combined with other generation sources or energy storages to provide continuous power generation to the electricity grid. To balance the generation gradients caused by passing clouds, the communication system needs to fulfill exigent timing constrains. Power plants in multi MW dimension may consist of thousands of sun trackers and could be spread over a range of more than one square kilometer. To monitor them in real-time and to visualize the incidents in the plants, an enormous amount of data is to be communicated.

Up to today, research institutes and CPV plant manufacturers have mainly been focusing their research on cell and module technology being the most challenging and cost intensive parts. This unilateral progress has caused a lack of optimized communication and control solutions. Designers of control applications need tools to compare and evaluate approaches. Modeling and simulation are common engineering methods to achieve quantitative statements for large-scale installation with passable effort. Different approaches can be developed, validated and compared rapidly.

However, to our knowledge, there is no model of sophisticated communication systems of large-scale CPV power plants. The preliminary work [2][3] discusses related work for research on CPV's communication systems generally, ranging from informatics to research on industrial applications with similar requirements. As this literature do not use OMNeT++ simulations, further resources of the OMNeT++ society have been considered. Such are accuracy related publications as [5] and publications focusing on large-scale networks as [7] and [6].

The objective of this work is to deliver a scalable model of the communication system of CPV power plants with the actual state of the art configuration using Ethernet. Based on this, the incidents should be understood and issues of large-scale systems identified. It should be used in the future as reference for comparing the state of the art with new topologies or technologies such as Wireless Mesh Networks (WMN) or Power Line Communication (PLC). Key parameters of the communication system such as the end-to-end (ETE) delay between plant control application and sun tracker should be determinated in the simulation. This work should enable research on new concepts like automatic configuration to validate them before being applied in the field. In this workshop contribution, the actual progress of the model's development is presented and the first results are outlined.

2. THE COMMUNICATION SYSTEM OF CPV POWER PLANTS

The size of CPV power plants has increased significantly during the last years. The largest plants in operation already reach a nominal power of $30.0MW_p$ and plants with more than $150.0MW_p$ are under construction or planned [8]. As the size increases, the quantity of network nodes being part of the power plant's communication system increases as well. Manufacturers usually use Ethernet for the IT infrastructure [9]. Since the cable length of Ethernet is usually limited to 100 meter, the power plants are divided into sections. The sections of such large-scale power plants are coupled via fibre optic lines. In some cases the topology of one section is a star. One central Ethernet switch concentrates the cables of all trackers and links them to the next section and the power plant control center. The drawback of this approach is that each tracker needs an individual cable to the central switch causing nonessential cable costs. To reduce redundant cabling, the star topology can be extended by chains. The extended star topology fits well to the topology of the power bus cabling when central inverters are used. This fitting is even more important than the reduction of cable length since groundwork costs are significantly higher. Figure 1 shows the extended star topology chaining sun trackers to one section of the power plant. This is the topology being implemented in the OMNeT++ model explained in Chapter 3. The degrees of freedom of the topology to compose a specific power plant are the number of sections, the quantity of sun trackers in west-east orientation per section and the quantity of trackers in north-south orientation.

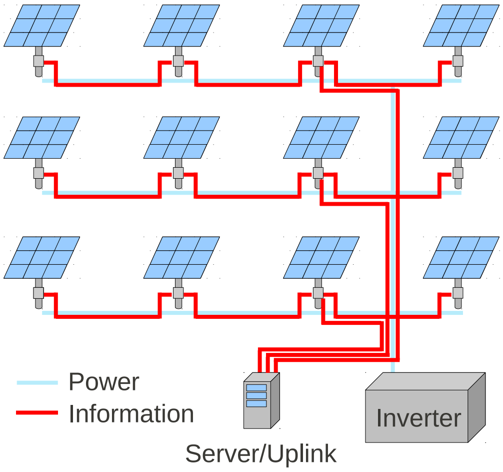

Figure 1: Topology of one section of the CPV plant

In addition to the topology, static IPv4 addresses are assigned to the communication devices. Several application protocols are used which are mostly based on Transmission Control Protocol (TCP) and sometimes User Datagram Protocol (UDP). Modbus TCP is one typical application layer protocol for measurement data of meteorological devices, power measurement and the control of inverters. But also proprietary protocols occur in CPV power plants. In particular, manufacturers of sun trackers bring their individual implementations. Usually the central power plant control application polls periodically every sun tracker and peripheral device to request latest state values or to send new set points. The duration of one polling cycle is an important parameter to determine the possibility to control the power plant dynamically. With the actual state of the work, the traffic of application protocols is represented by data of INET's TCPSessionApp.

3. THE OMNET++ MODEL

The OMNeT++ model of the CPV power plant uses the INET 2.0 Framework to generate a generic topology based on Ethernet. The model mainly consists of several NED files, a modular configuration and R scripts for the analysis. C++ modules will be implemented as well. But at the present state, C++ is only used for adding particular statistical variables to the TCPSessionApp of the INET Framework.

3.1 NED Files

The objective of the NED files is to provide a highly generic and flexible topology of the state of the art communication system described in Chapter 2. Therefore several standard modules of the INET library are used and some of them have been extended. The most important modules forming the model are SunTracker, BuildingBlock and Plant.

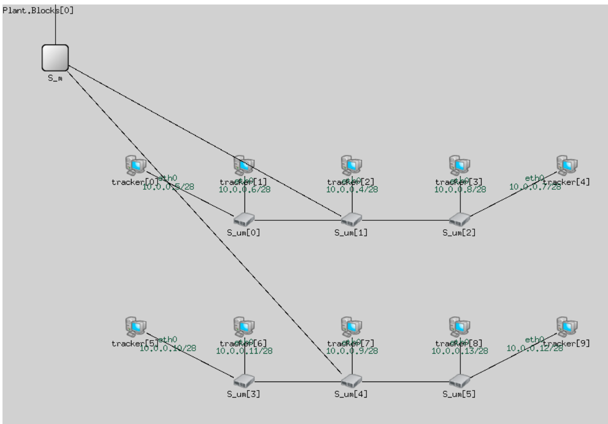

Figure 2: TCL/TK view of one BuildingBlock

The SunTracker extends the StandardHost offering parameters for automatic positioning in the TCL/TK user interface. In Figure 2 the SunTracker modules are implemented as tracker[*] instances. S_um[*] are usual EthernetSwitch modules, also extended with location variables.

The complete topology of one section in the power plant is generated by the BuildingBlock module. The BuildingBlock module has two input parameters to configure the quantity of sun trackers in west-east and in north-south orientation. Additionally, BuildingBlock modules have an index parameter. With this index parameter every sun tracker and switch of the complete power plant can be configured specifically. The individual configuration allows time-shifted transmissions. In a first attempt, time-shifted TCPSessionApp transmissions from every sun tracker to the central power plant control center are implemented in an extended BuildingBlock NED description. The time offset between every sun tracker is set constant.

The NED model allows to arrange the scale of the power plant model using a certain configuration. The three significant parameters therefore are Plant.numBlocks, Plant.Blocks [*].numTrackerEW and Plant.Blocks[*].numTrackerNS.

3.2 Configuration files (ini)

One exemplary use-case which should be accessed by the model is a power plant of 35 sections (BuilingBlock modules) while each consists of 60 sun trackers. With this configuration the simulation model creates 2,100 sun trackers and switches. It was observed that OMNeT++ simulations of this scale tend to generate a huge amount of data while being very time intensive. The output data needs to be restricted to only record the significant values for the actual research. For this purpose, the configuration is parted into two configuration files: one for small-scale compositions and one for such large-scale installations.

The small-scale configurations allow the usage of the OMNeT++ analysis tools. The sequence diagram of the event log, scalar observations or vector plots enable detailed understanding of incidents. The objective of small-scale simulations is to identify the relevant scalars and vectors to be recorded in the large-scale configuration. The small-scale reference design also facilitates fast development of NED files or C++ implementations when changes are not tested in time-consuming large simulations particularly.

The large-scale configuration, in contrast, only records the most relevant data. All large-scale simulations are intended to be analyzed by R scripts instead of using the internal OMNeT++ tools. Both configuration files use inheritance to achieve a high degree of clearness and flexibility.

3.3 Data analysis using R interface

As mentioned before, R scripts became necessary to analyze the huge amount of data experienced in large-scale simulations, when the OMNeT++ tools caused performance issues. Several scripts are implemented with different purposes. One default script performs a general analysis of the simulation output data of OMNeT++. It generates an output text file which lists the quantity of recorded scalars, modules and names. The standard script further counts the quantity of managed switches and calculates several total sums. Apart from that, the script creates an ordered list of several parameters which is also written to the text file. Parameters are the amount of sent and received bytes of hosts and switches on Media Access Control (MAC) layer.

In addition, there are several specific scripts for creating plots of particular vectors delivered by the standard script. Such are the quantity of received or sent bytes, the port speed, and the delay between the plant control center and each tracker.

4. RESULTS

The actual progress on the development of the OMNeT++ model allowed detailed understanding of the incidents happening in the state of the art communication systems of CPV power plants. Single interactions between the devices and communication layers could be reproduced and observed step-by-step. Also specific quantitative statements for the configuration of CPV power plants were produced with the actual model. The time of the TCP session establishment between each tracker and the power plant control center was calculated and illustrated particularly in Figure 3. Therefore a plant with 2,100 trackers, separated in 35 sections each with 60 trackers was simulated. The focus of this simulation was to investigate the influence of the tracker's position and the topology on the timing. For this purpose, the TCP session establishment between control center and each tracker was configured time shifted to prevent influences between simultaneous transmissions.

Figure 3 shows the TCP session establish time for each tracker (0 to 59) of a building block with this idealization. Out of the 35 building blocks only 5 were selected to display the trends clearly. In addition to the cable delays, the processing time of the switch's relay units and the processing delay of the StandardHost's IP layer were both set to values of $0.1ms$. For this configuration, TCP session establish

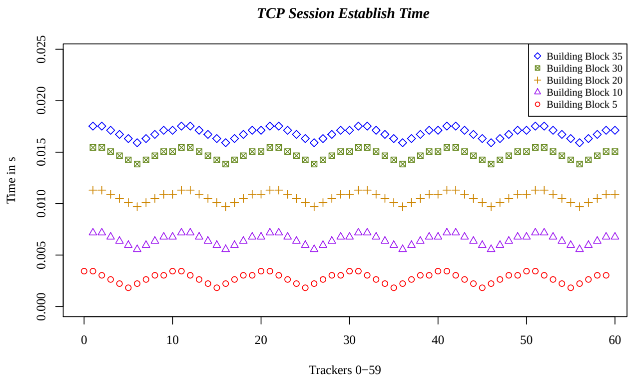

Figure 3: TCP session establish time

times ranged between 1.82ms and 17.5ms. The accumulated sum of all 2,100 TCP session establishments resulted in $20,6s$. This value indicates the absolute minimum of a polling cycle performed by the plant control center via TCP.

The second important variable is the data occurrence in the power plants. Therefore a simulation analyzed the transferred bytes on MAC layer. More than 5,000 entities were recorded in total since both, the sun trackers which were derived from the INET StandardHost module and Ethernet switches, were equipped with a MAC module. The highest data concentration was found at the managed switches coupling the building blocks which were close to the plant control center. The lowest data occurrence resulted in sun trackers located at the end of topological branches.

5. DISCUSSION

The results demonstrate the possibility of gaining quantitative statements of the communication system with impact on the design of the power plant control system. The detailed understanding and the experiences gained while implementing the model are already a great advantage for the designers of the plant control system.

In small-scale validation experiments performed in a testbed at Fraunhofer ISE it was observed that the first configuration of the simulation model was still very idealized regarding the timing. The delay of a simple TCP session establishment was about 20 times shorter in the simulation than in the measurement. The timing accuracy in the testbed could be improved when the parameters relayUnit.processingTime of switches and ip.procDelay of hosts were set to 1ms. The deviation between ping experiment and ping simulation in the testbed was then 8-15% instead of a factor of 20. Additionally to the testbed, further validation experiences in real power plants will be performed soon to adjust the delay parameters of the INET Framework more precisely. It is also necessary to consider simultaneous transmissions in the simulation to achieve more realistic quantitative timing results.

The model will be extended to generate more relevant statements. New mechanisms and protocols are to be developed such as an application running at the power plant control center and polling each tracker. Another objective of the further research is to compare different approaches. A layer 3 model should be developed in which the tracking control and the Ethernet switches are combined in unique embedded device [2]. Further tasks are IPv6 and the development of self-configuration mechanisms for communication and control system. However, even if further research is necessary, this workshop contribution shows the ongoing work on the OMNeT++ model for this industrial application of electricity generation. The first results are promising for future development in order to improve the control system and to make CPV power plants more competitive.

6. ACKNOWLEDGMENTS

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