Composition and Application of Power System Digital Twins Based on Ontological Modeling

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***Abstract*—The approach to create power system digital twins is presented by the example of energy supply of a geographically localized R&D facility. In this paper, the six-layer digital twin architecture is proposed and its prototype software implementation is described. The architecture consists of an ontological model, a digital single line diagram, electronic documentation, master data, load measurement data, and mathematical models and simulations. The paper describes problems and principles of ontological modeling of the prosumer infrastructure, including customer load, low-voltage distribution network sections, small-scale generation equipment, and electric energy storage devices. The optimal configuration of the hybrid power supply system with renewable energy sources was computed using the digital twin that was composed according to the presented approach. For machine-readable representation of the digital twin, the ontological modeling language OWL is used.**

Keywords—modeling, digital twin, ontology, generative design, distributed energy resources, Internet of Energy

I. Introduction

Nowadays, the world goes through the so-called energy transition, viz. a transformation of the energy infrastructure towards the “3D's” (decarbonization, digitalization, decentralization) [1]. The transformation implies a significant technological and organizational development of microgrids - high-tech active small-scale power systems with local generation on renewable energy sources and energy storages [2]. The most expected result of such transformation is the Internet of Energy (IoEN) [3][4] - an infrastructure organized as a decentralized network of direct transactional energy, information and economic interaction, functioning on principles that are similar to the global computer network Internet. The Internet of energy infrastructure has the form of a network of cells encapsulating the functions of generation, consumption, and storage of energy resources [5]. The Internet of energy concept in Russia is being developed by the Infrastructure Center “EnergyNet” within the framework of the National Technology Initiative [6]. The development includes a reference architecture and various pilot implementations as well as the necessary legal and regulatory framework.

Information components comprise one of the key parts of the Internet of Energy architecture. According to modern trends, the main principle of their organization is the development of digital twins (DT), viz. virtual copies of energy facilities that can reliably reproduce the state and behavior of the originals in real time [7]. A proper set of digital twins can completely represent the entire energy infrastructure. Only such a set is able to ensure the manageability, stability, and optimization of the energy infrastructure under decentralized distributed control. It is particularly important that diverse facilities’ stakeholders identically and correctly name and interpret the concepts with which the digital twin operates. For this purpose, the ontological model of the energy infrastructure is employed as a basis for the digital twin; a significant experience for the development of such ontological models has been accumulated [8][9].

Still, various problems associated with the development, updating, and application of digital twins in the energy sector are not yet solved and turn to be the subjects of intensive research. In general, the conceptual basis of the digital design of power systems is still at the level of traditional Computer-Aided Design (CAD) and Product Lifecycle Management (PLM) systems of the beginning of the XXI century [10]. The technologies for development and application of digital twins have been adopted from mechanical engineering; however, they adapt in the power industry with great difficulties. They require cumbersome expensive software tools and highly qualified personnel [11][12]. At the same time, there is a lack of unambiguously interpretable reliable data in standard machine-readable formats, adequate mathematical models, and appropriate digital equipment [13]. The technologies such as Generative Design [14], allowing to automatically find the optimal design solutions for power supply [15] are being developed very slowly. These problems are particularly acute for the life cycle of the mass small consumers’ power systems of low voltage levels (0.4 kV), who usually have neither powerful software nor highly qualified staff.

The authors’ aim is to develop approaches to solve these problems for facilities belonging to the digital decentralized decarbonated energy sector. For reaching this goal, the research work has been performed on the appropriate testbed. The work consisted in testing the principles of digital modeling and generative design of power systems using the prototype software

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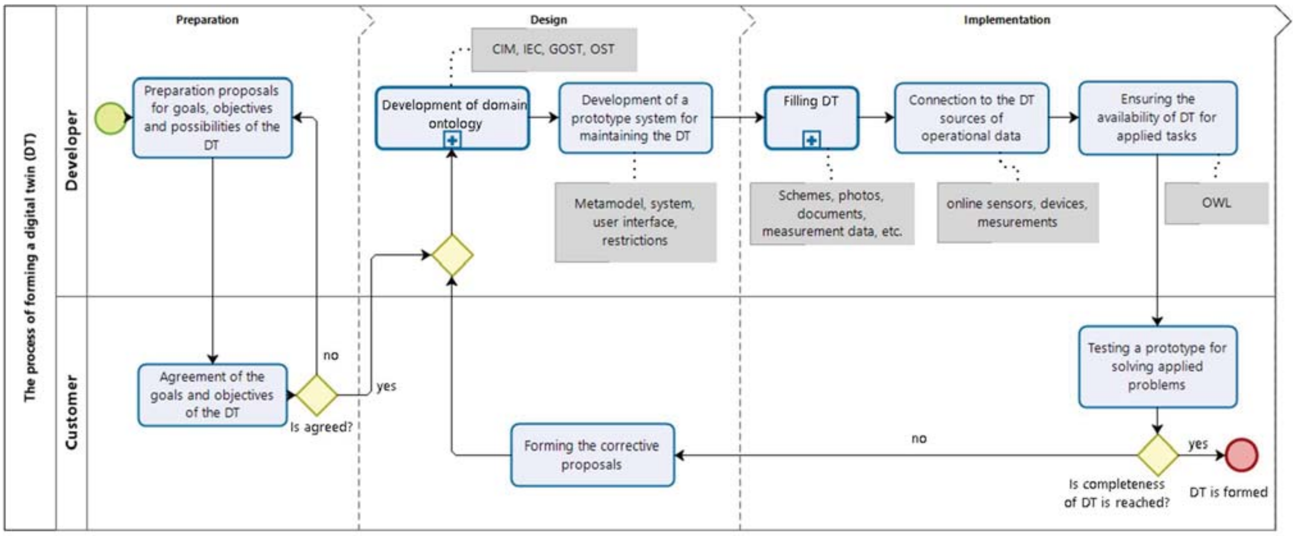

Fig. 1. The process of forming a digital twin.

tools. The work involved the selection of a testbed, the automated development of the digital twin of its power system, and the automatic search for the optimal configuration of a hybrid renewable energy system (HRES) containing generating equipment on renewable energy sources and energy storages. The results and outcomes from the work are presented in this paper.

II. The Selection of a Testbed

For representative testing of the new principles and technologies for automating the life cycle of complex facilities, a proper testbed must be reasonably selected. The testbed facility should allow to apply the examined intellectual products in all key aspects. The implementer of testing shouldn't "get lost" among numerous components of the object, irrelevant details, technological lag artifacts, and organizational issues in obtaining access permissions. The test results must be sufficient to provide the outcomes and recommendations on the use and improvement of examined products; these outcomes and recommendations must be substantiated by measurements and experiments that has actually been taken at the facility.

This work aims at evaluating and applying the principles of digital modeling and generative design of the new generation power systems. The task is to form and apply a digital twin of the testbed, according to the process that is shown in Figure 1. The intended objective of the twin is chosen to be an automatic search for the optimal configuration of the HRES for the facility, which is one of the classical generative design problems.

The work has started with composing a primary list of potential facilities, among which a testbed must be selected. The list included such facilities as an educational and scientific complex (university department), a gas station, and a household (cottage). At the first stage of the selection process, a brief description of each type of facility was compiled. Then the criteria of importance for selecting the facility were formed. These criteria characterize the facility as a candidate energy cell of the Internet of Energy architecture. They should be relevant for all types of facilities and have an identifiable influence on the complexity, quality, and representativeness of the results. The examples of such criteria are: territorial proximity of the object to the project environment, availability of digital customer meters with a sufficient degree of disaggregation, connection to the centralized power grid, adaptability for installing on-site generation on renewable energy sources, and variability of load profiles.

Finally, the suitability of each criterion for solving the research problem of this paper was evaluated and quantitatively scored in points separately for each facility with the help of subject area experts. Summing up the scores, the educational and scientific complex (university department) has received the highest grade and therefore has been selected as the testbed.

III. The Power System Digital Twin Architecture

The digital twin of a facility can be represented as a system of interconnected computer models that are capable to reliably perform the following actions:

- display the state of the object in real time;
- predict the object's behavior in normal and abnormal conditions;
- determine the control actions on the object.

So digital twins are designed to simulate all sorts of actions that can potentially affect the facility during its full life cycle (including those that were not actually performed). At the same time, they must be able to predict the aftermath of these actions and to evaluate the potential counteractions against negative consequences. Accordingly, the main component of the digital twin is a set of mathematical, information, economical, computational, simulation, and neural network models that describe all aspects of the object's behavior. There exist powerful calibration mechanisms to increase the reliability of these models, including those based on machine learning [16]. In order to provide convenient access to the models that form the digital twin, they are often represented as services [17]. The

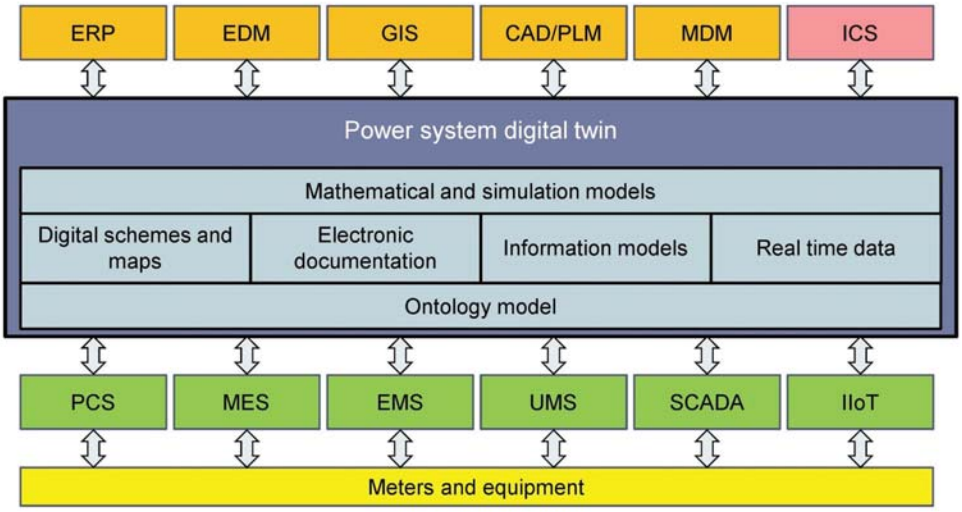

Fig. 2. The power system digital twin architecture.

service oriented architecture hides the details of the implementation of the models and this is particularly convenient for application in distributed systems with decentralized control, such as the Internet of Energy.

The main use cases for digital twins in power systems are:

1) evaluation and forecasting the generation, consumption, and storing the energy resources;

2) evaluation and forecasting the grid segments capacity;

3) development and virtual testing the control device settings, emergency modes, and switching between modes;

4) predictive health monitoring of the equipment, assessment of accident rate and maintenance needs;

5) calibration and verification of models and control algorithms;

6) validation and evaluation of design decisions;

7) training the energy facilities personnel.

A classical digital twin of a base type (Baseline Twin [18]) was created for the power system of the testbed. The following sections of this paper will show that it allowed to capture the following subset of the above-mentioned use cases: (1) in full; (5) in terms of specifying the consumption profile of individual devices according to the integral data collected from customer meters installed in the department rooms (i.e. disaggregation); (6) in terms of automatic search for the optimal configuration of a HRES. It was also confirmed that mathematical models should be supplied with up-to-date input data from certain basic information components in a machine-readable format. The components describe a facility in all possible aspects, so their data are vital for correct performance of mathematical models. To avoid any kind of interpretation errors, the data were structured according to the ontological model. The data is supplied in an automatic mode to ensure that mathematical models always have an up-to-date undistorted picture of the structure and state of the facility.

Based on the authors' extensive experience in the design of large information and control systems for the power industry [19], the following basic information components of a digital twin were identified:

- digital schemes and maps;
- electronic documentation;
- information models;
- real time data.

The developed architecture of the digital twin, including its structure and interconnections with adjacent automated systems, is shown in Figure 2.

For complex facilities, there is a fundamental problem associated with assembling their holistic digital twins from the twins of composing components. It is essentially required to reproduce virtually the process of assembling the power system of a facility by means of information and mathematical models, taking into account principles that regulate their connection to each other. One promising approach to solve this problem was proposed on the basis of the mathematical device of category theory [20]. The structure scheme of the facility is represented by a diagram in a suitable category that consists of algebraic models of system units and their interrelationships. Then the so-called colimit of the diagram (an algebraic analogue of the assembly) is calculated. Such algebraic representation for information models is presented in [21].

IV. Ontological Modeling of the Prosumer Infrastructure

The widespread common information models (CIM), which normally serve as a source of terms and relationships, are mainly focused on large energy facilities: power plants, power lines, substations. The ontological modeling of geographically localized energy facilities of low power consumption is more difficult task due to high variability of their energy devices and equipment. Several subtasks should be solved at the process of

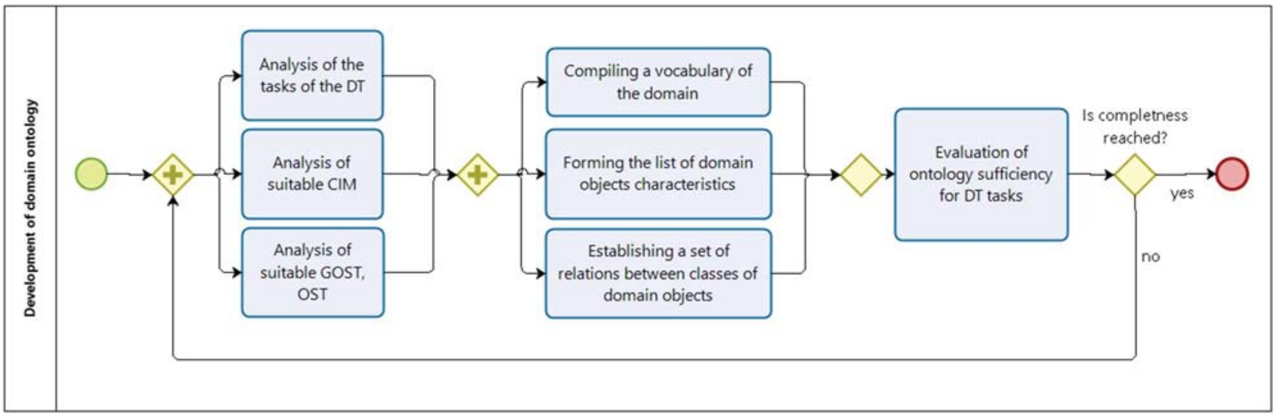

Fig. 3. The process of the domain ontology development.

modeling: the subject area analysis, entities identification, determination of entities structure and types of properties, establishing the relationships between entities, validating the created model in practical tasks. The process of the ontology development is depicted in Figure 3.

In the course of the current work, this process was performed on an iterative-incremental basis. One iteration consists of actions necessary to compose and test the next version of the ontology. The iterations are repeated as necessary to adjust or refine the ontology. Testing the ontology consists of the following steps: configuring a metamodel for an information model of the testbed facility; entering data that describe the testbed facility into the information model; exporting this model for a subsequent search for the optimal HRES configuration; and finally, checking the semantic correctness and sufficiency of the model data.

A software tool, based on the product called Nrjpack, was developed to maintain the information models and other digital twin components. The tool architecture is built upon the metamodel, viz. the description of information entities, properties, and relationships between them. This design decision allowed to automate the following routine programmer's tasks:

- composition of the user interface forms for data creating, reading, updating, and deleting operations;
- automatic formation of the structure and content of the database;
- export of the information model for subsequent feeding to mathematical and simulation models.

Thereby, the development of a software tool for maintaining a digital twin boils down to setting up a metamodel according to the ontology. Such an approach significantly reduces the time and labor costs required to perform iterative-incremental development cycles of the twin, comparing to the traditional domain-driven design (DDD) approach [22]. The reason is that traditionally the elements of ontology are represented as classes and objects that are described explicitly in the source code. In this case, when changing the ontology, it is not enough to reconfigure the system through the user interface: one needs to change the source code, recompile, test, and install the new version of the software. The presented maintaining tool allows to overcome this drawback.

The tool is built on the CQRS (command query responsibility segregation) architecture [23]. It implies that the user's requests are divided into two independent streams: queries and commands. By making changes to the information model or to the metamodel, the user actually forms a change request, to which the tool responds by changing the data structure or filling it via forming the corresponding events. It should be noted that the CRQS architecture is applied not only to the information model entities, but also to the metamodel entities. This feature makes possible to highlight events that are aimed to change the structure of the information model, not just the content. Such events are "directed" into a separate stream. One option to handle events is to implement an information model as a relational database. Such an approach is traditional for information systems with high load. Herewith, it is particularly attractive for the tasks of creating and maintaining a digital twin, because it allows to compose different relational projections optimized for different applications of the twin.

The developed software tool is able to automatically export a complete set of information about the facility; the creation and exporting the information set are implemented on the basis of the metamodel. The information is exported into a file in the standard ontological modeling language OWL (Ontology Web Language) recommended by the international consortium of web technologies W3C [24]. As it has already been mentioned, export is based on the metamodel and therefore automatically reflects changes in the ontology. The OWL language allows to simplify integration with arbitrary mathematical and simulation models and hence to maximize the scope of application of the digital twin.

V. Search for the Optimal Configuration of the HRES

The instructive use case for the developed digital models of the testbed is an automatic search for the optimal configuration of the HRES. The optimal configuration implies such combination of generation equipment units and energy storage devices that leads to the greatest operational effect comparing to passive power supply from the traditional electricity grid. Different effect criteria exist: economic (savings on annual cost of energy supply); electrical (power quality); environmental (amount of carbon emissions) [25]. Therefore, both technical and economic aspects are important in modeling HRES for the chosen use case. There exist various methods of solving such optimization problems mathematically [26][27]. One example is the genetic algorithms, viz. heuristic search algorithms that randomly select initial values of the parameters, and then further combine and vary those using mechanisms similar to the natural selection [28]. The genetic algorithm could potentially be used to search for the optimal HRES configuration of the testbed, but the authors did not have enough computational resources for running the algorithm over the developed model. For that reason, instead of homemade developments, the more "lightweight" software product HOMER Pro [29] was used. It was designed to find economically suboptimal solutions for power supply of microgrids or isolated territories, which matches the goals of the study. Thus, the set of mathematical models of the digital twin was assembled. Its structure and interconnection with the ontological model of the testbed are shown in Figure 4; specifically, the model set consists of the following parts:

- the HOMER Pro model to determine the optimal configuration of the HRES components;
- the dynamic model in Matlab Simulink for evaluation of the chosen configuration;
- the set of scripts in Python and Matlab for connecting all the models to each other.

The HOMER Pro model selects the suboptimal ratio of generation equipment units and storage devices to ensure the supply of the given load profile. The load profile is formed according to the information model. The results of HOMER Pro model computations are exported to files of Excel format for feeding to a dynamic model of the power system. The dynamic model was created on the basis of the existing microgrid model from the Matlab database [30], and was revised accordingly for the chosen use cases of the digital twin of the testbed with on-site HRES. The layout of the model is shown in Figure 5. The model automatically creates an HRES configuration from the output files of the HOMER Pro product. It includes also a centralized power grid, which either provides power to the load (if not enough power is produced by on-site generation and storages of HRES), or receives back the excess power (e.g. from generation on renewable sources). The simulation period is controlled by the user; the model is well fitted for testing the performance of equipment on a given day. The data defining the work scenario for the components are imported from the information model and external services like National Renewable Energy Laboratory (NREL) [31]. These data include the load profiles of each individual device and the weather data (e.g. solar radiation and wind speed) for the selected time period. The model outputs a state chart for each equipment unit, displaying various electric parameters and profiles of generation and consumption in time.

As was mentioned above, the lack of tools for automatic data synchronization between the layers and adjacent systems is one of the main challenges in assembling the holistic digital twin. To bridge this gap, the scripts on Python and Matlab have been written, of which the following two are the most important.

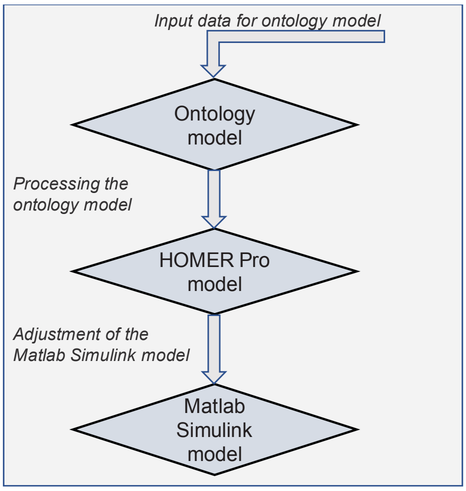

Fig. 4. The set of mathematical models of the digital twin and its interconnection with the ontology model.

The first script processes the OWL/XML file that is automatically exported from the software tool for maintaining the information components of the digital twin. The script forms the hourly consumption profile for each energy load (device) specified in the information model and the total profile for all energy loads. The consumption profile is calculated based on the information about the nominal energy consumption and the operation mode of the load. All this information is contained in the OWL/XML file. The calculated profile is an estimate and should be calibrated by actual consumption data from digital customer meters. In practice, a meter (that is located, for example, at the entrance to the room) most often measures only total consumption of several diverse energy consuming devices. Therefore, it is required to disaggregate the data, i.e. to distribute the total consumption data between the devices [32]. The data from meters are compared with the calculated profiles, after which the disaggregation is estimated by the nature of changes in consumption (such as a notable sharp increase or decrease in power). As a result, realistic consumption profiles for each device are formed, which are then fed to the HOMER Pro model.

The second script automatically adjusts the Matlab Simulink dynamic model according to the results from the HOMER Pro model computations. During the adjustment, the Simulink model is being programmatically changed. The script initializes the required number of blocks and elements inside the model, as well as electrical and information signals between them, according to the information model of the facility and the calculated HRES configuration by the HOMER Pro. This results in an up-to-date model that simulates the power system (Figure 5).

So the user participation in digital twin development is essentially limited and is necessary only at a few stages of the process. The user needs to enter the information about energy consuming devices (quantity, arrangement by rooms, nominal power consumption, operation mode or schedule of use) to the web interface of the developed software tool for maintaining the digital twin. Then the user needs to manually launch the HOMER Pro product. The full-scale digital twin of the power

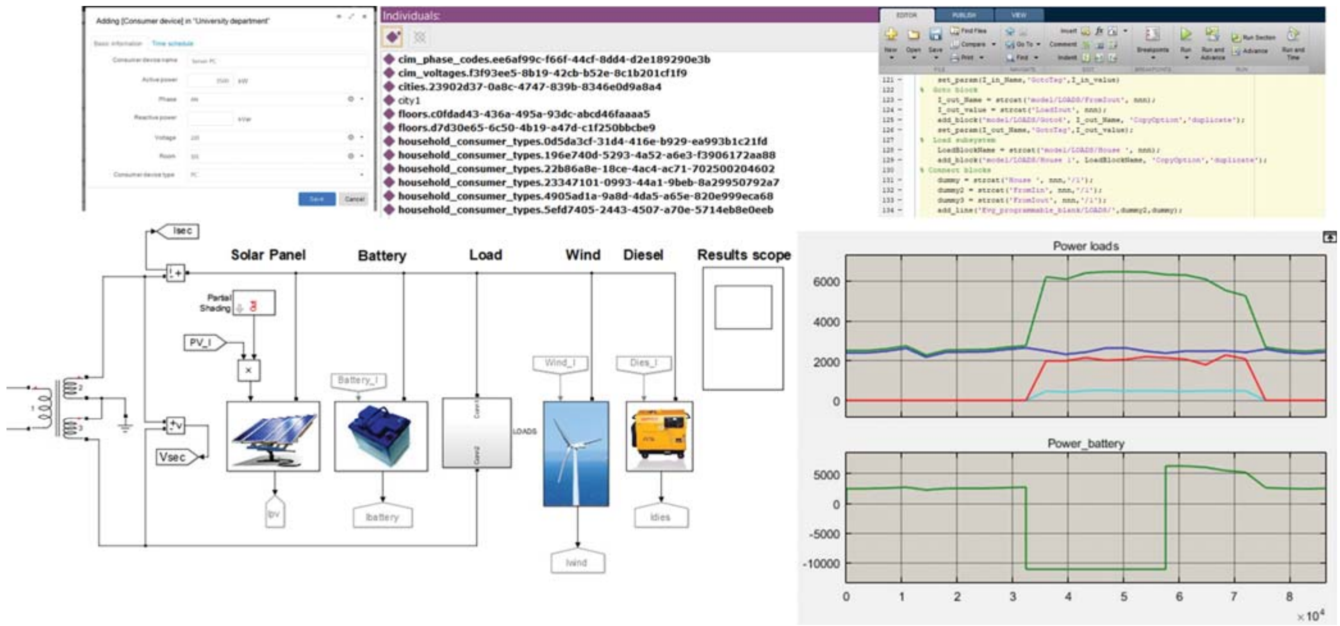

Fig. 5. Creating and adjusting the dynamic model in Matlab Simulink according to the ontology model. The Results scope window displays the simulation results and arbitrary electrical parameters.

system is then composed fully automatically. The final result is represented as a dynamic model, which allows to evaluate the functioning of the power system under arbitrary conditions and scenarios. The specific electrical parameters (power, voltage or currents) can be observed for any component as well as for the power system as a whole.

VI. Conclusion

The paper has shown that the testbed selection is the important preliminary stage for testing the principles of digital modeling and generative design of new generation power systems. The testbed must be a representative prototype of the structural element of the future digital decentralized decarbonated energy infrastructure. An educational and scientific complex (university department) was selected as an appropriate facility. It allowed to properly perform the process of automated development of a digital twin and automatic search for the optimal configuration of the hybrid power supply system. This task has been solved without excessive labor and time expenses with the help of properly configured prototype software tools. A classical baseline digital twin of the power system of a typical low-voltage prosumer was built using the development principles described in this paper. Based on the gathered experience and theoretical studies, the power system digital twin architecture was developed and validated on practice. Six components of the architecture were identified: the ontological model, digital schemes and maps, electronic documentation, information models (master data), real time data, mathematical and simulation models. The obtained results are considered as fundamental for designing the information basis for future power systems.

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