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Digital twins application in control systems for distributed generation of heat and electric energy

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Abstract By the emergence of distributed energy resources, with their associated communication and control complexities, there is a need for an efficient platform that can digest all the incoming data and ensure the reliable operation of the power system, which can be achieved by using digital twins. The paper discusses the advantages of using digital twins in the development of control systems and operation of distributed heat and electric power generation facilities. The possibilities of using the digital doubles for increasing the efficiency of the considered objects is presented as the example of optimizing the configuration of a control system of solar collectors in the presence of heat losses in pipelines of the external circuit. Further, the total balance consumed and generated electric and heat energy are presented. Examples of algorithms for protecting equipment to improve security are given, and the possibilities of improving the reliability of distributed power systems are considered. The system use of the digital twins provides the possibility of developing and debugging control algorithms, which increase the efficiency, reliability and safety of control objects, including distributed thermal and electrical power generation complexes.

Keywords: Solar collectors; Heat pump; Renewable energy complex; Digital doubles; Efficiency; Reliability; Safety

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1 Introduction

Currently, there is a rapid development of thermal and electrical energy generation facilities based on distributed plants using renewable energy sources. For example, according to [1, 2] for the period 2004–2017, the increase in the share of renewable energy sources in heating and cooling was in Malta at the level of 72.4%, whereas in the UK it was 69.81% and in Hungary – 44.91%, respectively. The change in the share of electricity from renewable energy sources in that period amounted in Malta to 140.3%, in Cyprus to 101.1%, and in the UK to 71.9%. In addition, in 2004–2017, the change in the share of renewable energy sources in transport amounted in Finland to 113.78%, whereas in Malta to 115.52%, and Belgium to 96.53%, respectively. In [3] the current status and advancement of digital twin-driven smart manufacturing was reviewed to propose a reference model for the context of Industry 4.0. Previous studies on the technologies for the development of a digital twin for smart manufacturing were exploited to the generation volumes to current weather parameters does not provide stable production for small objects oriented to a single type of renewable energy [4]. One of the solutions to the problem of improving the reliability of power supply of such facilities is the use of complexes using several different types of retention and splicing complex, supplemented, if necessary, by such installations as gas-piston or gas turbine generators implemented according to a bivalent scheme. The introduction of such complexes involves a number of tasks to improve reliability, efficiency and safety, the solution of which can be entrusted to a large extent to the complex management system. At the same time, the development and adjustment of complex control algorithms requires, as a rule, preliminary calculations using mathematical models of the system. Over the last decades, energy and resource efficient has become a significant issue for industries which aimed to reduce the pollution [5, 6].

It should be noted that a large number of works are devoted to the development of mathematical models of elements of distributed energy systems. For example in the work [7] the author consider improving the energy efficiency of solar power plants by improving photodetectors, using automatic positioning systems and optimizing the control processes of module positioning systems. In the field of geothermal energy sources, [8] describes a mathematical model of a soil heat pump based conditioning system.

Application of complex models in development of retention and splicing complex control systems allows to increase efficiency of energy production, which is noted in works [9–11]. At the same time, the development of such models, taking into account the action of the whole complex with the synchronization of the mathematical description with the actual indicators of the real object, as well as the addition of auxiliary information on the characteristics of the equipment, allow us to switch to the formation of the so-called digital twins. This provides the ability to manage the entire life cycle of the equipment [12, 13]. The digital twin combines information about the performance of the object, its detailed mathematical model, the parameters of which are determined using the real data. The use of digital twin technology in the field of renewable energy is quite promising and is used throughout the world. For example, the Predix platform [14] when creating digital doubles of gas turbines, as well as [15] to estimate and predict the residual life of wind generators. The research propose a methodology and simulation results for developing a data-driven digital twins operation applied on industrial system in the context of the Industry 4.0 in thermal and electrical energy generation facilities. It aims to uncover interrelations between operational business and technical system to enhance operational strategies.

2 Method – digital twin in power system

Electricity 4.0, digital twins for electric utilities and automation can significantly help address challenges of the electricity supply chain, from generation, transmission to distribution and storage. In this research the digital twin (DT) was used for control and distribution in power systems, which uses both previous and current data of applied sensors, and data combined with modeling and simulation. Digital twin refers to the mapping of the physical asset models in a digital platform, where a virtual digital replica model is created. For such systems the number of state variables, n, is equal to the number of independent energy storage elements in the system. The values of the state variables at any time, t, specify the energy of each energy storage element within the system and therefore the total system energy, and the time derivatives of the state variables determine the rate of change of the system energy. Figure 1 depicts the cooling system model. Furthermore, the values of the system state variables at any time provide sufficient information to determine the values of all other variables in the system at that time.

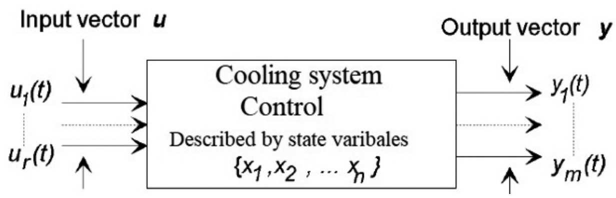

Figure 1: Proposed model of the cooling system.

The digital twin model is proposed to be a multi-purpose function. It can be used by many applications. According to the required solution, the DT model is defined by the sampling time, the known inputs and the desired outputs. The previous energy cyber-physical system (ECPS) and cyber twins can be hybridized to replicate the cyber-physical system's behavior as follows:

$$\dot{T}_M = \frac{UA}{(mCp)_M}(T_M - T_m) + \frac{qH_M}{(mCp)_M}\,, \tag{1}$$

$$\dot{T}_M = \frac{UA}{(mCp)_m}(T_m - T_A) + \frac{UA}{(mCp)_m}(T_M - T_m) + \frac{qH_m}{(mCp)_m}\,, \tag{2}$$

where T and m represents the temperature and mass, Cp is the specific heat, UA and qH are the generated heat and heat distribution rate respectively. The subscripts M, m and A indexes represent the maximum, minimum, and ambient temperatures, and the overdot denotes differentiation with respect to time. It can be summarized as $\dot{X} = Ax + Bu$ and $Y = Cx + Du$ in the state space form for the control system which is presented in Fig. 2, where S^{-1} present the transfer function to the state space form.

$$\begin{aligned}
\begin{bmatrix} \dot{T}_M \\ \dot{T}_m \end{bmatrix} &= \begin{bmatrix} -\dfrac{UA_{M/m}}{(mCp)_M} & \dfrac{UA_{M/m}}{(mCp)_M} \\ \dfrac{UA_{M/m}}{(mCp)_m} & \dfrac{UA_m}{(mCp)_m} - \dfrac{UA_M}{(mCp)_m} \end{bmatrix} \begin{bmatrix} T_M \\ T_m \end{bmatrix} \\
&\quad + \begin{bmatrix} \dfrac{1}{(mCp)_M} & 0 \\ 0 & \dfrac{1}{(mCp)_m} \end{bmatrix} \begin{bmatrix} qH_M \\ qH_m \end{bmatrix},
\end{aligned} \tag{3}$$

$$\begin{bmatrix} \dot{T}_M \\ \dot{T}_m \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} T_M \\ T_m \end{bmatrix}.$$

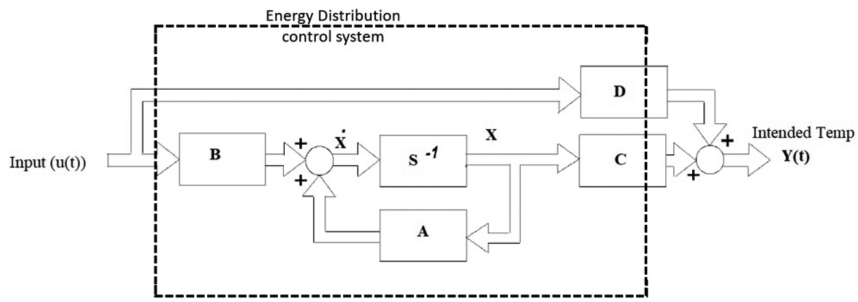

Figure 2: Digital twin in energy control and distribution.

By employing the DT system in the proposed state space, the current data including temperature rate, maximum and minimum temperatures are collected to regulate the intended temperature with minimum cost and energy. In addition, based on the data of long-term operation, complex descriptions of elements of the interconnected retention and splicing complex intended for the production of thermal and electrical energy, including wind plants, photovoltaic panels, solar collectors, and heat pumps have been prepared. The use of developed DT made it possible to develop algorithms for managing renewable energy systems that provide a given level of economy, reliability and safety.

3 Results

3.1 Efficiency increasing of thermal energy generation by solar collectors

Consider the diagram of the two-circuit solar collector (Fig. 3), where cold water is heated in the storage tank (ST) due to the heat energy of the coolant moved by the circulation pump through the solar collector. Circulation pump operation is controlled by the relay law with hysteresis.

In the proposed design of the cooling system, the main parameter is the size and, more precisely, the intended cooling capability determined by the storage tank. The currently determined cooling capacity achievement is one main objective for the operational storage tank control. Main applicable management levers are the installed equipment, which can tuned the air and water to the required proportion. Cooling capacity rate (Q_{ST}), as the intended output of the cooling and electric power intense ($PI_{t,e}$), is

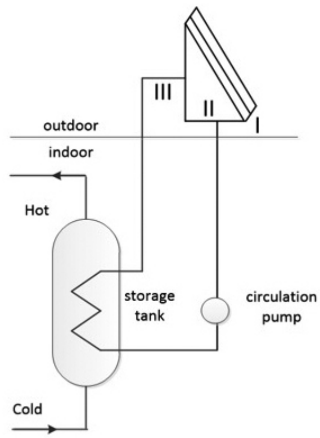

Figure 3: Solar heating unit diagram.

presented in the form

$$\mathrm{EER}_{ST} = \frac{\mathrm{Output}_{ST}}{\mathrm{Input}_{ST}} = \frac{Q_{ST}}{PI_{t,e}} \,. \tag{4}$$

Sections of coolant circuit pipelines located outdoors (I and III in Fig. 3) in winter season have heat losses that may affect the system operation. With a large length of these sections, when the volume of the coolant in them is comparable to the volume of the coolant in the manifold (II in Fig. 3), the opposite effect of cooling water in the storage tank can be observed. When the circulation pump is switched on, the cold coolant of section I enters manifold II, cools the temperature sensor located in it, which leads to the pump shutdown. At the same time heated heat carrier from manifold, displaced into section III, does not reach storage tank and does not transfer heat to heated water.

Optimized calculation of settings of relay algorithm of pump operation allows to increase efficiency of installation. Let's take a look at this problem. At the constant water temperature in the storage tank, the operating time, t'', of the circulation pump is determined by the cooling rate of the temperature transducer, and can be found according to Kondratiev's theorem [16]

$$t'' = \frac{\ln|T_m - T_{ct}| - \ln|T_m - T_{ct} - \Delta''_T|}{K\alpha} \,, \tag{5}$$

where: T_m, T_{ct} – manifold and coolant temperature, Δ''_T – assigned temperature difference (set point) at which circulation pump is switched off,

α – coefficient of temperature conductivity, K – is the proportionality factor. For a cylinder of finite length l and radius r, the proportionality factor K is defined as

$$K = \left[\left(\frac{2.405}{r} \right)^2 + \left(\frac{\pi}{l} \right)^2 \right]^{-1} . \tag{6}$$

The average water temperature by volume, $\overline{T}_{wt}$, in the storage tank is determined by

$$\overline{T_{wt_i}} = \frac{\dfrac{t''\pi H T_{at}}{R_{rh}} + \left[G_{fw} c_{fw} \left(T_{ct} - \theta \right) + G_c c_c T_{hwt} \right] t'' + m_{hw} c_c \overline{T_{wt_{i-1}}}}{m_{hw} c_c + \left(G_c c_c + G_{fw} c_{fw} \right) t'' + \dfrac{t''\pi H}{R_{rh}}} , \tag{7}$$

where: H – height of the storage tank, T_{at} – ambient air temperature, R_{rh} – linear thermal resistance of heat transfer, G_{fw} – mass flow rate of water, c_{fw} – specific heat capacity of water G_c – mass flow rate of coolant, c_c – specific heat capacity of coolant, T_{ct} – coolant temperature after manifold, θ – difference of temperatures of the heat carrier and heated water, T_{hwt} – heated water temperature, m_{hw} – mass of heated water, i – iteration number.

The duration of the heating of the coolant, t', to the set point of switching on the circulation pump, (Δ'_T, during insolation, E, can be determined by the expression

$$t' = \frac{V \rho_C c_{fw} \left(\Delta'_T + \overline{T_{wt}} - T_m \right)}{E} , \tag{8}$$

where: V – coolant volume in manifold, ρ_C – coolant density, T_m – manifold temperature.

Generally, the DT consists of three main components. namely the DT shadow, DT model and DT updating. The original features and state updates of an asset are collected to form the live digital replica of a physical or a cyber-asset. The behavioral characteristics and the dynamical features of a thing are mathematically modelled, and the model is enhanced by the last shadow states. The DT model is updated based on the working states and conditions of a thing.

By combining the updated sensors data for the temperature differences, and the proposed model in Eq. (1), the DT can replicate the real system digitally. The heat distribution is mathematically formulated to describe the static and dynamic features of the thing, and enhanced by full or partial information from the edge parts. In this section the performance of the DT in control systems for distributed generation of heat and electric energy to improve efficiency, are evaluated. For this purpose in the first step, the graph of the sensor cooling time, t, as the surface is shown in Fig. 4.

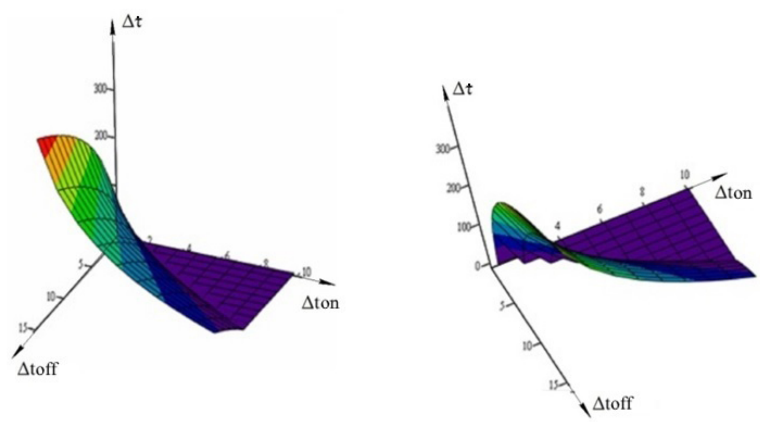

Figure 4: Dependence of sensor cooling time on specified temperatures for pump switching on and off.

Calculations show that in winter it is necessary to increase the circulation pump switching set point, while reducing hysteresis. This increases the frequency of pump activation, reducing the cooling time of the coolant in the pipes (zones I and II, Fig. 3). The use of the proposed method of calculating the operation time of the circulation pump when modeling water heating processes in solar water heaters allows finding the most effective values of the settings at various ambient air temperature values. Figure 5

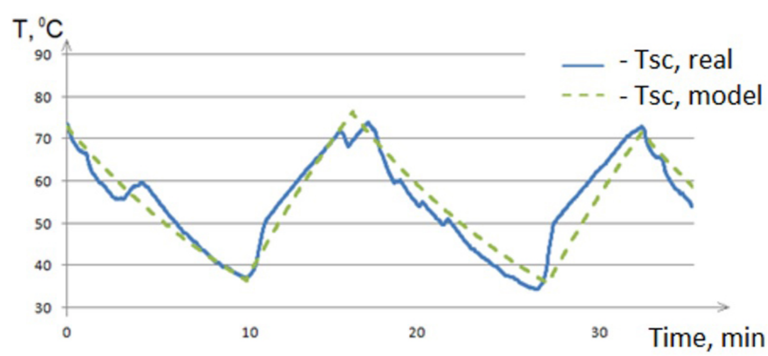

Figure 5: Temperature change in the manifold of a solar collector.

shows the comparison of temperature change graphs in the manifold of a solar collector in the model calculation (Tsc, model) and in reality in the optimized settings (Tsc, real).

3.2 Safety and efficiency by digital twin

To increase efficiency of the entire renewable energy complex, the algorithm for accounting for all energy flows (production and consumption of thermal and electrical energy) has been tested as a part of the information support of the complex control system. The data obtained at the accounting stage allows to build a balance of energy throughout the complex, which ensures the search for the most optimal operating modes and the allocation of energy overspending zones. Based on the available data, for example, the values of main parameters of the efficiency of the ground heat pump operating as part of the complex under consideration are obtained, where heat transformation coefficient μ is equal to 5.301, Carnot inverse cycle transformation factor equal to 7.78, and exergetic efficiency of the heat pump equal to 0.2837.

The value of effective coefficient of transformation of heat of the soil heat pump unit taking into account an electric power expense on work of auxiliary systems, such as circulation pumps, control system, etc. is experimentally defined. The effective coefficient of transformation is always a lower passport for most thermal pumps. For this installation, the passport value of the transformation coefficient is 2.97, and the experimentally obtained effective value is 2.65, which is 12% less. Taking into account the effective value of the transformation coefficient will allow for more accurate design calculations when selecting equipment, as well as more rational formation of the control law during the operation of plants.

The complex control system described in [9] provides a higher efficiency by estimating the forecast of energy consumption and generation by selecting the optimal combination of currently involved energy sources. Also, in the safety the DT for energy distribution improves the safety and reliability of retention and splicing complex.

4 Improvement of safety of retention and splicing complexes

To ensure the safety of equipment and personnel of renewable energy sources systems, the authors of the work proposed and tested algorithms for protecting and blocking equipment elements. Storage tank frost protection is necessary for defrost protection of the tank in case of the solar collector frost protection, since the storage tank is always filled with water. If the protection is introduced, then when the temperature of the tank is lower than the set point of actuation. In such case heating by additional heat sources (electrical heater and heat pump) will be turned on. Observed hysteresis is 5°C.

Storage tank overheating protection is required in addition to mechanical protection by the storage tank safety team in order to avoid high pressure in the tank and damage to the tank. If the protection is introduced, then if the tank temperature is higher than the actuation setpoint equal to 95°C, the circulation pump will be turned off. In such case hysteresis is 10°C.

Protection against increased hot water temperature is required to protect personnel from injuries caused by high water temperature at the outlet of the storage tank. According to the requirements of regulatory documents, the temperature should not exceed 60°C. If the protection is introduced, then in case the water temperature in the storage tanks increases above the protection actuation setpoint equal to 60°C, the three-way valve after the storage tank switches to remove water to the drain.

Protection against depressurization of the external circuit of the system is required to protect the equipment, primarily circulation pumps, from the damage during depressurization of the external circuit of the system and coolant leakage. It is controlled by the value of pressure in the circuit. In case of pressure decrease is lower than a protection operation setting equal to 0.01 MPa, the circulation pump forcibly stops, valves after the circulation pump are forcibly closed.

5 Improving reliability of retention and splicing complexes

Reliability of power supply to consumers in normal operation mode of plants is ensured by complex approach to selection of various sources, as well as application of control algorithms, which take into account optimal operation modes taking into account forecast of consumption and generation [9, 17].

The reliability of the generating system from the point of view of preventing emergency situations can traditionally be ensured by implementing algorithms for protecting and blocking equipment. The algorithms of operational recording of the operating time of the complex equipment to ensure timely repair and maintenance has been tested. An electronic simulator [18], which simulates the operation of soil heat pump plants, in order to develop the skills of the personnel to operate the equipment of generating complexes has been implemented. The mathematical description of the system elements used in the simulator is synchronized with the characteristics of the real complex, which provides a high level of identity of the system reactions to control actions.

The implementation of the tasks described above ensured the formation of a comprehensive digital description of the system elements, updated synchronously with data of a real object, that is, formation of digital twins of equipment. Description of each element includes information such as equipment name, manufacturer, date of manufacture, date of commissioning, technological designation, power consumption, allowable temperature range, assigned resource, actual resource, information on repairs and maintenance performed, dynamic characteristics, and control algorithms.

6 Conclusion

The research proposed a methodology and simulation results for developing a data-driven digital twins operation applied on industrial system in the context of the Industry 4.0 in thermal and electrical energy generation facilities. It aimed to uncover interrelations between operational business and technical system to enhance operational strategies. The findings showed that the accumulation of information about operated objects allows you to create a complex system of interconnected digital doubles. The system used of the digital twin to provide the possibility of developing and debugging control algorithms that increase the efficiency, reliability and safety of control objects, including distributed thermal and electrical power generation complexes. The results showed the ability of the proposed models to be a live digital replica of future power systems. The proposed digital twin tries to minimize the energy to enhance the performance of the temperature cooling system with considering the safety. It was concluded that by proposed digital twin, the energy saved up to 10% and with accuracy of the 95% in overall for real time performance.

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