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QUASI-DYNAMIC MODEL OF THE INTERCONNECTED POWER SYSTEM OF UKRAINE FOR A FREQUENCY STABILITY STUDY

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Significant integration of renewables into Ukraine's interconnected power system (IPS) requires developing the appropriate quasi-dynamic (QD) model to study power system operation in such conditions. The work aims to create a QD model of the IPS of Ukraine considering renewables and consumption profiles of the Ukrainian IPS for the winter and summer character days. The corresponding approach to such a model development is presented in the paper. The load flow series simulation results based on the quasi-dynamic approach are also shown. Additionally, the frequency stability study results for the Ukrainian power system are depicted. Ref. 6, fig. 6.
Keywords: quasi-dynamic model, interconnected power system, frequency stability, generation, load, simulation.

The significant installed capacity of the renewables and the development of the power system increase the demand for the accuracy of the power system model. Currently, the common practice is a simulation of the power system operation only for some character regimes, i.e., for winter and summer peak and off-peak. Such an approach allows the definition of the voltage levels and loading of the network elements only for such regimes. However, the obtained results do not identify the duration of these abnormal situations (voltage violations and elements overloadings). Thus, the quasi-dynamic (QD) model is needed to be developed for the required time frame to define the duration of such critical regimes and to identify the appropriate measures to mitigate them [1]. As some individual components of the QD Model were developed and well described [1], the purpose of this paper is a development of the complex QD model (on the example of IPS of Ukraine) considering the various renewable generations (including PV plants and windfarms), hydraulic and thermal power plants.

In the paper, the QD model of the interconnected power system (IPS) of Ukraine in DIgSILENT PowerFactory software has been developed. The need for such a model is caused by the integration of the IPS of Ukraine to ENTSO-e and the significant increase of the renewable capacity in the generation structure of the Ukrainian IPS [2]. Besides, one of the essential tasks is a frequency stability study of the IPS of Ukraine operating synchronously with ENTSO-e [3, 4].

The developed QD model covers the winter (including 24-hour-profile patterns) plus summer days (24-hour-curve). Thus, the total time frame covers 24+24=48-hour points. Below, the QD model development approach on the example of the winter day is presented, and the approach for the summer day is similar. It should be noted that the generation, load, and other data have been collected and used for the target year (due to the nondisclosure agreement and security reasons, some data are not displayed in the figures). The diagram describing the process of QD model development in PowerFactory software is depicted in Fig. 1.

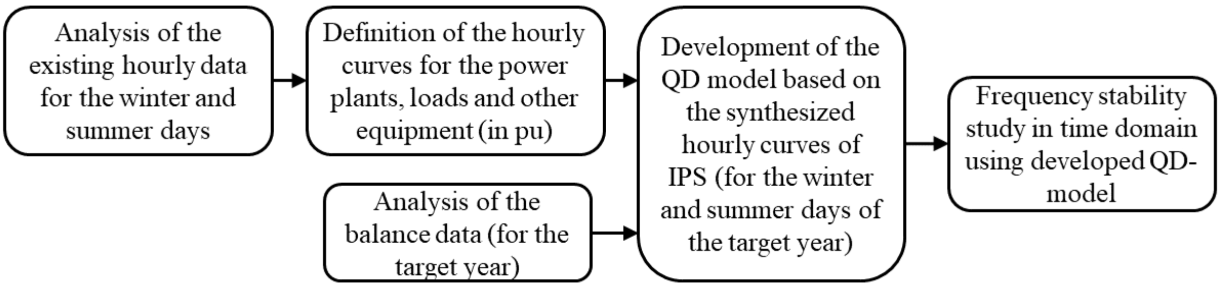

Fig. 1

The developed QD model of IPS of Ukraine includes the following data:

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- generation schedules for the individual generators;
- load consumption curves;
- generation pattern of the renewable energy sources;
- position of the shunt reactor switches (switch-on or switch-off);
- position of the on-load tap-changers (OLTC) of the transformers.

Additional data on actual active power flows through the interface are also used to validate the developed QD model.

The initial data for the QD-model are generation profiles of the nuclear, thermal, and hydro-power plants and generation of the PV plants and windfarms (Fig. 1). Additionally, load profiles and mentioned above data should also be analyzed as well. Such an approach allows defining hourly curves for the generation power of the power plants, consumption (in per unit), and other statuses (switches, OLTC positions, statuses of the main equipment, etc.). Further, the mentioned data are used to create the synthesized hourly data (considering balances for the target year) for the QD model of the IPS of Ukraine (for the winter and summer days). As a result, an obtained QD model can be used for the frequency stability study for the 24-hour series or the specified hour.

It should be noted that for the *i*-time point, the balances of the active and reactive power must be provided. In particular, the balance of the active power can be presented as:

$$P_{\text{gen.sched.}i} + P_{\text{gen.bal.}i} = P_{\text{load.}i} + P_{\text{loss.}i},\ i = 1\ldots n, \quad (1)$$

where: $P_{\text{gen.sched.}i}$ is a scheduled generation of the power plants covering the consumption of the power system; $P_{\text{gen.bal.}i}$ is a power providing the active power balance in the power system; $P_{\text{load.}i}$ is power system load (i.e., during the day); $P_{\text{loss.}i}$ defines losses of the active power. Thus, as (1) indicate, the active power balances are provided by the component $P_{\text{gen.bal.}i}$, which can be defined as follows:

$$P_{\text{gen.bal.}i} = P_{\text{load.}i} + P_{\text{loss.}i} - P_{\text{gen.sched.}i},\ i = 1\ldots n. \quad (2)$$

A consumption pattern has been synthesized for the target year to define a load curve, considering the consumption prognosis and prospective load profiles. Respectively, the load curve in absolute units (in MW) can be obtained by multiplying the power consumption values in p.u. by the maximum consumption value $P_{\max}$ for winter and summer days. The synthesized load profile for the winter day of the target year is presented in Fig. 2. As seen in Fig. 2, the minimum load is observed at 4:00, and the maximum load is at 19:00.

The appropriate generation structure has been determined to provide coverage of the consumption in IPS of Ukraine. Brief information on the power plant categories covering the consumption is provided below.

Power plants of Category 1. This category of power plants is presented by the nuclear power plants, which operate at the base of the load curve, and their generation is constant during the day.

Power plants of Category 2. PV plants and wind farms present this generation category. Considering the initial data, the appropriate generation curves of these power plants have been synthesized for the target winter and summer days [5, 6]. The resulting generation curves for PV plants and wind farms are depicted in Fig. 3 and 4, respectively. The generation of the PV plants has a traditional form with peak generation at midday; at the same time, the generation of the wind farms is more uniform due to the geographic distribution of the wind farms in the whole IPS of Ukraine. Due to the stochastic nature of PV plants and wind farms, the generation of these renewables is an additional disturbance

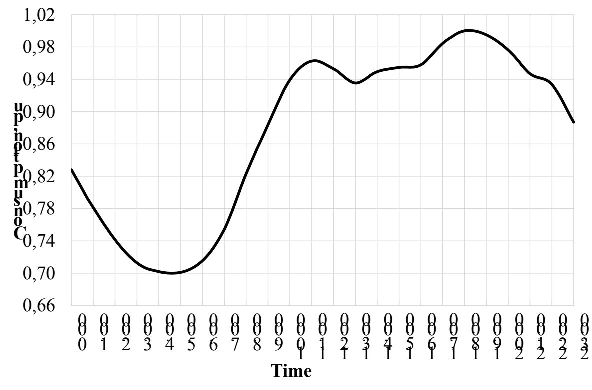

Fig. 2

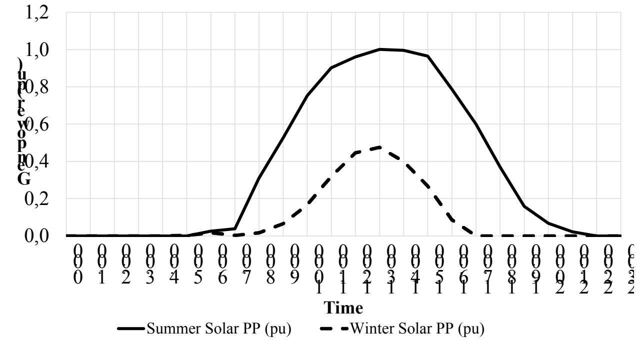

Fig. 3

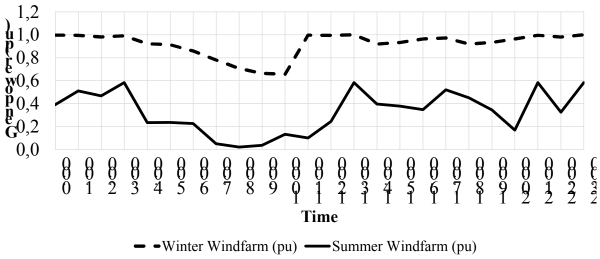

Fig. 4

that must be covered by the generation of the "traditional" power plants.

Power plants of Category 3. This category is presented by the generators of thermal power plants (TPPs). All TPPs were set by appropriate hourly schedules in relative units considering technological constraints on the operational limits of the units. In the QD model, two types of hourly curves were determined for the winter and summer days. The first curve type was applied to those units that are not switched off from the grid during the day. The second curve type of the TPP generation was used to simulate the cases of the generator disconnection from the grid during the day. It is necessary to consider the generator disconnection from the network during the minimum demand and its operation for the rest hours of the day.

Power plants of Category 4. This category is presented by hydropower plants (HPP) and power storage power plants (PSPP). Conventionally, this group of power plants can be divided into two types. Their schedule defines the generation of power plants of the first type during the day. The second type of power plant is presented by HPPs participating in the secondary frequency control. Thus, these HPPs aim to balance the power system between generation and consumption, considering these regulating power plants' active power operation limits. This generation corresponds to the component $P_{\text{gen.bal.}i}$ in (2).

The generation structure of the IPS of Ukraine, considering certain types of power plants, is presented in Fig. 5. As seen in Fig. 5, the total consumption in IPS of Ukraine is covered by thermal and hydropower plants.

The appropriate software module has been developed to adapt the developed QD model to study the power system stability in the time domain. This module was implemented as DPL-Script (build-in program language in PowerFactory) that converts QD initial data allowing to research the frequency stability (in "seconds" time frame) using the hourly resolution QD model of IPS of Ukraine. It should be noted that the developed QD model can be used to simulate the frequency stability of the IPS of Ukraine. To perform such calculations, the model was extended by considering the governor characteristics of the generating units participating in the primary frequency control, dynamic loads, and the detailed models of the under-frequency load-shedding relays.

The feature of this model is performing frequency stability study not only for the minimum and maximum loads but also for other hours considering current loads. This model is implemented in DIgSILENT PowerFactory software and can be used to study the IPS operation in load flow calculations and in time domain simulations for the specified hour or time frame. As an example, in Fig. 6**Ошибка! Источник ссылки не найден.**, the simulation results of the frequency stability are presented for the winter day in the case of the 1000 MW generating unit disconnection at the nuclear power plant. Such calculations are performed using the developed QD model of IPS of Ukraine. In Fig. 6, the frequency in IPS of Ukraine is depicted for each hour of the winter day (a total of 24 frequency curves). As seen, the sudden frequency change is observed below 49.2 Hz. This is due to UFLS action to prevent the operation of the special protection automatics of the generating units at nuclear power plants.

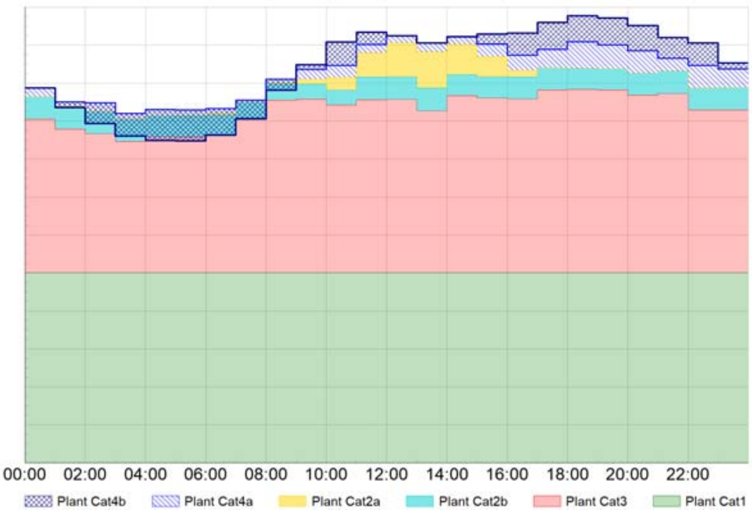

Fig. 5

Thus, the QD model of IPS of Ukraine for the winter and summer target days has been developed in the PowerFactory software. The model can be used to study the operation of the

Ukrainian IPS in load flow calculations. Besides, the frequency stability and primary frequency control simulation can also be performed. It should be noted that the developed QD model can also be used to study secondary frequency control. However, it requires consideration of the automatic generation control model. The model of such a control system will be developed and integrated into the QD model in future steps.

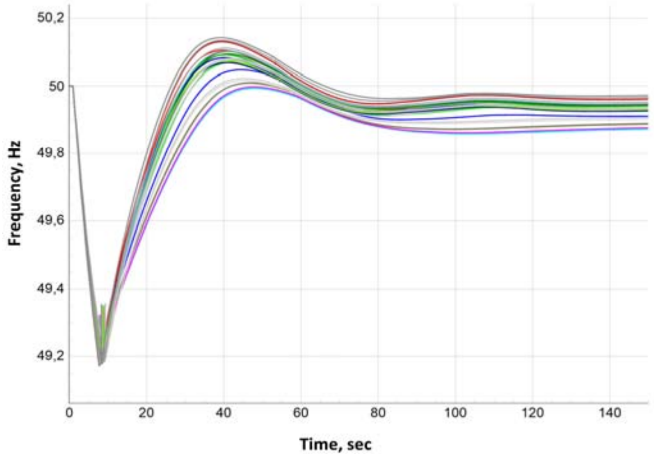

Fig. 6

Роботу виконано за держбюджетною темою: Розвиток елементів теорії, розроблення нових методів розрахунку та створення засобів для підвищення надійності та енергоефективності режимів і технологічних процесів в електроенергетичних та електротехнічних системах (шифр: Режим-1), що виконується *за постановою Президії НАН України від 22.12.2021 №419 в рамках договору № 3-22 від 04.01.2022 р. Державний реєстраційний номер роботи 0122U001494, КПКВК* 6541230.

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КВАЗІДИНАМІЧНА МОДЕЛЬ ОЕС УКРАЇНИ ДЛЯ ДОСЛІДЖЕННЯ СТІЙКОСТІ ЗА ЧАСТОТОЮ

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Значна інтеграція відновлюваних джерел енергії в об'єднану енергетичну систему (ОЕС) України вимагає створення відповідної квазідинамічної моделі з метою дослідження режимів енергосистеми за таких умов. Метою роботи є розробка квазідинамічної моделі ОЕС України з урахуванням графіків генерації та споживання для характерних зимових та літніх днів. Представлено підхід зі створення зазначеної моделі. Крім того, також подано результати квазідинамічного моделювання усталених режимів ОЕС України. Додатково наведено результати дослідження стійкості ОЕС України за частотою з використанням створеної моделі вітчизняної ОЕС. Бібл. 6, рис. 6.

Ключові слова: квазідинамічна модель, об'єднана енергосистема, стійкість за частотою, генерація, споживання, моделювання.

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