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OPTIMIZATION OF THE FUNCTIONING OF THE RENEWABLE ENERGY SOURCES IN THE LOCAL ELECTRICAL SYSTEMS

Monograph

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О-66

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The monograph considers the problem of the functioning of local power systems with different types of renewable energy sources (RES) in power grids by optimizing their connection schemes, as well as automation of a part of control functions, namely, optimal control of RES regimes, taking into account the peculiarities of their conversion of primary energy and electrical connections. The monograph is intended for specialists in the field of mathematical modeling and optimization of the work of renewable energy sources in distribution electrical networks, and may also be useful for students and graduate students of the appropriate direction.

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CONTENT

INTRODUCTION

Modern global trends to decentralize power consumers that are associated with increasing cost of traditional fuel and manifested in the increasing proportion of distributed electricity production from renewable energy sources (RES), lead to complications planning regimes of electric power systems (EPS) and their operational management [1–3]. In addition, the combination of the mentioned above processes with economic power engineering reform – implementation of bilateral agreements – virtually prevent to organize the effective functioning of the EPS without improving their information infrastructure with a gradual transition to the concept of intellectual power networks (Smart Grid) [4–6].

State support for development of renewable energy stimulates research on the design and operation of renewable energy to enhance energy security and reduce the impact of energy on the environment. However, the issue of transportation of electricity produced renewable energy and functioning regional electricity networks (REN) in the new operating conditions are often neglected in the design phase of renewables and place of their accession to power networks (PN).

Lack of research about the design and operation of renewable energy in modern conditions and their impact on modes of electric EM, inconsistency of the specified main equipment to the needs of these sources, lack of information about the typical decisions regarding remedies and automate process electricity production of electricity prevents make informed design decisions during their development, moreover, can't effectively exploit them [7–10]. Thus important is the development of methodical, information and technical support of operation. Important in this regard is the complexity and methodological unity in decision making to improve the performance of renewable energy in their work in electric networks.

In the design scheme of power delivery from the source to the end user raises the need to harmonize their work with the system, of which implemented the central power. That scheme should meet the requirements of reliability for ensure stable power supply and connectivity to provide RES as close to the center of power consumption that will ensure minimum power losses at its transportation.

Based on this, one can identify a number of important technical aspects of the development of renewable energy in local electric systems, which currently are not sufficiently investigated:

- research and analysis of regulations on the operation of renewable energy sources in the local electric system based on the concept of Smart Grid;
- analysis of the known methods of optimization of electrical networks from renewable energy sources;
- development of methods for determining optimal installed capacity and optimal placement of renewable energy sources in the local electrical system using the integrated optimality criterion;
- development of optimization method daily modes of generating renewable according to predictable schedule loads the local electrical system (LES);
- development of mathematical models of optimum configuration LES conditions and method and optimal control laws schemes issuing power of renewable energy sources;
- development of optimization algorithms installed capacity of renewables and places joining in the local electrical system;
- development of optimization algorithm to daily modes of RES generation according to the predictable schedule loads of LES;
- development of optimal control algorithm of changing configuration scheme for issuing renewable electricity by the criterion of minimum power losses.

Thus, the actual task of optimization of RES in local electric systems solve a problem of design – to determine the optimal installed capacity, and as operational problem – to optimize the daily mode of generating RES and circuits issuance of power electrical energy by local electric networks with RES. This can increase the profitability of energy utilities and power generating companies by improving performance characteristics of electrical equipment in LES. The aim of our work is to improve the efficiency of renewable energy in electrical distribution networks by improving the methods and means of optimizing transport electricity produced.

LEGEND

ACS	– automatic control system;
AUC	– automated control system;
CU	– condensing units;
DB	– data base;
DES	– distributed energy sources;
e.f.	– electromotive force;
EPS	– electric power system;
ES	– electric system;
HPP	– hydraulic power plant;
LES	– local electric system;
LESR	– local electric systems reconfiguration;
OIC	– operative-information complex;
PL	– power line;
PSPS	– pumped storage power station;
PN	– power networks;
RE	– renewable energy;
REN	– region electric network;
SH	– small hydro;
SP	– software package;
SPP	– solar power plant (direct power conversion);
WF	– wind farm.

1 OPTIMIZATION PROBLEMS IN ELECTRIC NETWORKS WITH RENEWABLE ENERGY

1.1 Problems of forming intellectual electric networks according to Smart Grid concept

Current trends in world power generation industry development are directed on electric networks modernization. Most of the world industrially developed countries comprehend the necessity of increasing the power efficiency in the context of global warming problems. So, they stimulate development of alternative and renewable energy, as well as increase of automatic optimization and control in electric networks, improvement of relay protection facilities etc. [4].

Development of power generation industry set the problem of gradual transition from traditional technologies that expect use of electric networks centralized generating to basically new solution that is directed to wide application of distributed energy sources and active networks able to provide services on transfer, keeping and transformation of electrical power. Active electric systems are able to adapt quickly to variable needs of interested parties – owners, consumers, vendors. They are considered to be the key element of infrastructure of the future "intellectual" power systems. At present all the aspects of creating "intellectual" power systems are viewed within the Smart Grid concept, the most known and popular concept for electric networks modernization [5–6].

Such a concept is characterized by bilateral electrical energy and information streams for creating automated, widely branched distribution grid. Within it, information exchange goes on between communication domains of generating, transfer, distribution and consumption of electric power that are physically presented by systems of production automation and control for each domain [11]. Besides bilateral electrical energy streams and information exchange, this concept provides implementation of current control, protection and functioning optimization of all interacting elements. Those elements include powerful generators and renewable energy sources that are connected with industrial consumers, energy-storage units as well as end users using to main and distributed networks.

It is worth to accentuate that Smart Grid is not just new energy technologies, but also modern information and communication technologies for billing, e-commerce, access and administration control in the networks of various scale, data modeling and storage, virtualization, computer safety, distributed information computing, collection, processing and transfer real-time [22]. In fact, Smart Grid should be considered not as a single technology, but as a complex approach and methods of creating large-scale «intellectual» enterprises that function on base of new technologic platform and provide a wide range of services with use of information and power technologies.

Specialists think [23] that use of modern management technologies together with wide use of new information and communication technologies will give the possibility to support supply and demand in "intellectual" power systems on the level of a single device. Smart Grid will enable users to take part in power system functioning consciously, at that using assets in power generation industry will improve, economic efficiency will increase, as also quality of electric power and stability of power systems against unendorsed external influence. Finally, transition to "intellectual" power systems will push to development of new types of production and services, and formation of new markets.

1.1.1 Principles of local electric systems with renewable energy functioning in the Smart Grid concept

Principles of Smart Grid operation consist in integration and automation of generation, transfer and consumption processes. In general case Smart Grid technologies are understood as a set of software and hardware tools that contribute increase of electric power transfer efficiency. Efficiency is comprehended as:

- decentralization of functions generating and controlling electric energy and information streams in a power system;
- reducing of expenses for arranging power transmission system;
- rapid elimination problem;
- possibility to transfer electric power and information in two directions that is considered an important condition for the concept of distributed power generation industry and use of renewable energy.

Electric network based on Smart Grid concept unites two subsystems:

- electric power transfer subsystem;
- information exchange subsystem.

So, besides conventional power lines, information connections that join all participants of electric power market are introduced. Rough membership of market participants and connection between them is shown on fig. 1.1.

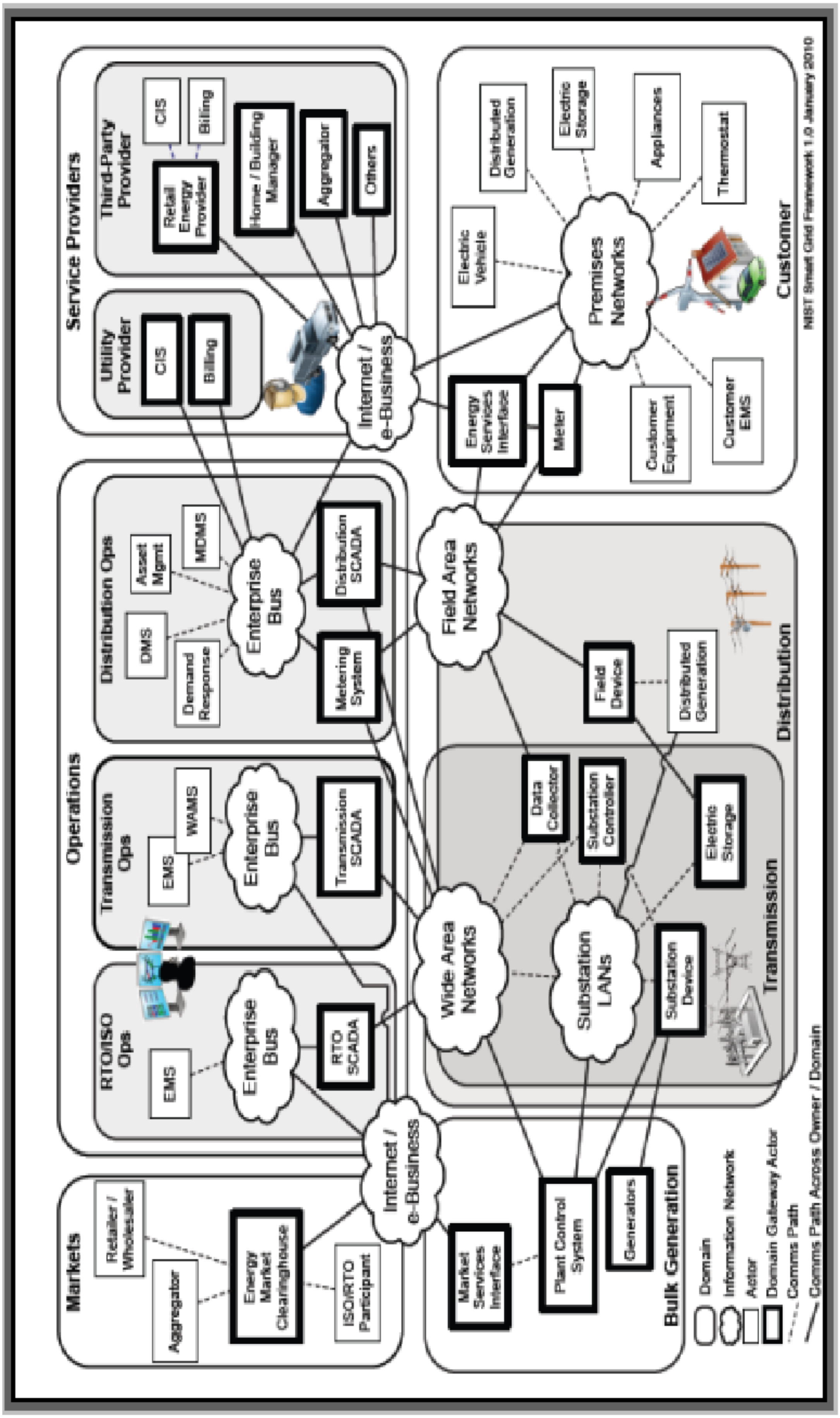

Figure 1.1 – Power system conceptual model

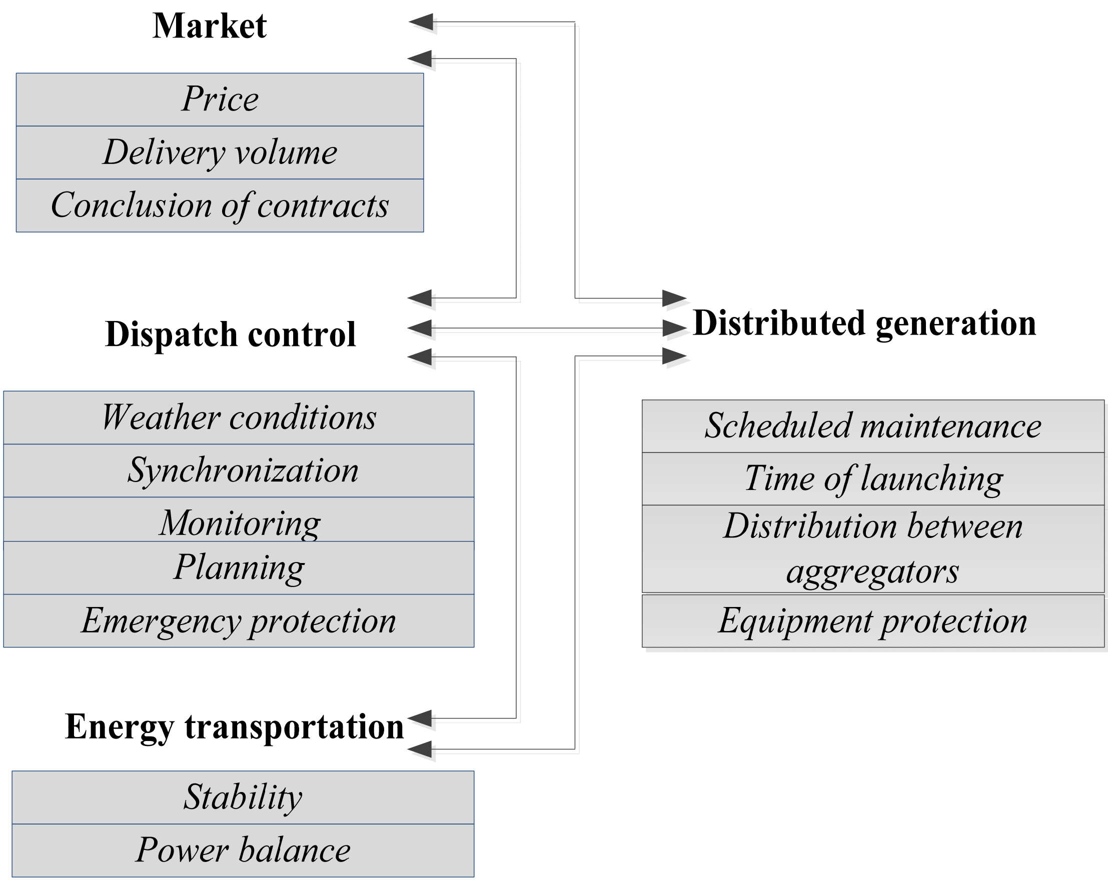

Figure 1.2 – Main functions of separate Smart Grid domains related to power generation due to renewable energy

Domain "Distributed generation" joins power stations, including RE of various types that deliver electric power to distributed electric grids. Its main job is to increase efficiency of electric power production by such sources. Special complexities occur on the way of optimizing wind farms and solar power plants as their modes are defined by stochastic influence of the environment. At this it is almost impossible to store primary energy (as, for example, in case of small HPP). The described domain relates to information streams with domains of control, power market functioning arrangement, and also with energy transportation domain. Information connection with the last one is the most important as the transportation domain functionally fulfills, together with other domains, data collection and processing, equipment protection, operating optimization and other.

Information connections allow to take into consideration operational specialties of different power stations that use RE, especially WF and SPP, where the process of electric power production has a number of technical and organizational peculiarities. Information connections with the domain «Market» allow to coordinate tasks of EPS with affirmed delivery volumes of electric power by terms of bilateral contracts, power market conjunction, correcting prices on electric power supplies and other system services.

1.1.2 Standardization of intellectual local power systems functioning at their integration into systems of centralized power supply

Today many world countries has a set of Smart Grid standards for means of relay protection, control and monitoring of main and distributed networks [24–32]. Among them special attention is paid to standards related to connection of renewable energy sources of distributed generation for parallel work with existing electric power systems. These standards are technologically neutral and universal for all types of RE up to 10 MVA and regulate technical specification to electric power systems with renewable sources of generation. Standards include general requirements to RE at normal and emergency modes, requirements to voltage quality indicators, separate and parallel work with electric power system, requirements to connection and synchronization of RE generators, as well as specifications and requirements to design, production, assembling, putting into operation and periodic tests.

There are about hundred standards that relate to Smart Grid. Among them – IEC standards ("Standards for power quality" and "Flicker Standards"), CSA standards (CAN3-C235-83, 107.1/UL1741, C22.2, C.22.3, C22.1), IEEEP2030 standards and other. In complex with these standards, principles of providing interoperability to power technologies, information technologies with elements of power systems, automation of end users and users loading devices are considered. The main standard that regulates RE connection to parallel work is the standard of the Institute of Electrical and Electronics Engineers (IEEE 1547) [33]. The current standard sets up criteria and requirements for connecting RE with EPS. System of IEEE 1547 standards includes a number of documents concerned with different aspects of providing interaction and coherency between distributed resources, integrated to the composition of power systems, and consists of parts:

- IEEE 1547.1 – standard for the general procedure of accordance of connecting RE to a power system.
- IEEE 1547.2 – provides detailed instructions of connection to parallel work.

- IEEE 1547.3 – requirements to information exchange, RE monitoring and control.
- IEEE 1547.4 – requirements to equipment and its exploitation in separate power systems with RE.
- IEEE 1547.5 – assigned to RE with the power higher than 10 MVA.
- IEEE 1547.6 – practical aspects of connecting RE to distributed grids.

Nowadays the process of connecting to parallel work of RE to Ukraine's power systems does not have any clear branch regulatory guide or standard. That is why growth of RE quantity leads to worsening of technical problems regarding arrangement of their parallel work in power system – providing consistency of operation, quality of electric power, arranging dispatch control, including control of separating RE from power system, synchronizing RE with power system.

Parallel work of RE in power grids is partially regulated by rules of connecting electricity-generating equipment to power grids, approved by regulation of National Energy and Utilities Regulatory Commission dated by 14.12.2005 with changes and attachments dated by 20.09.2007 [34]. The regulation includes just organizational moments of connecting electricity-generating equipment destined for electric power production. So, technical specifications of connecting RE to power systems are regulated by a number of regulatory documents, all-Union State Standards and Ukraine State Standards. With the aim to verify the possibility to use the experience of foreign countries, it is sufficient to compare technical specifications of IEEE 1547 standard, Germany standards [35], project of requirements of connecting RE in Ukraine [36] and acting all-Union State Standard 13109-97 «Quality standard for electric power in the systems of electricity supply of general purpose» [37] that is basic for Ukraine's energetics. Comparative analysis of requirements to quality of electric power according to provided regulatory documents is shown in table 1.1

Comparative analysis shows on appropriateness of solving a complex of tasks on RE functioning optimization in local power systems considering indicators of quality and loss of electric power with further conversion to a single standard. This standard will regulate connection to parallel RE work in Ukraine taking into account the strategy for developing power systems. This will expand opportunities to use RE and users' resources, as well as allow to perform LES functioning optimization taking into consideration improvement of interaction between all system's subjects in real time.

Table 1.1 – Comparative analysis of electric power quality indicators

Indicator	Specifications according to regulatory document			
	IEEE 1547	All-Union State Standard 13109-97	Project of requirements to connection of RE in Ukraine	Standards in Germany
Frequency deviation	Allowable frequency deviation in RE should not exceed the value from –0.2 to +0.5 GHz in synchronized systems.	Frequency deviation in synchronized systems of power supply should not exceed ± 0.2 GHz; in separate systems of power supply deviation makes up ± 1 GHz.	Frequency should retain between 49.6 (allowable critical decrease of frequency) and 50 GHz (allowable normal increase of frequency).	Frequency should retain between 47.5 (allowable critical decrease of frequency) and 51.5 GHz (allowable normal increase of frequency).
Harmonics	Maximum harmonics component of current makes up 4 % for odd harmonics $n \le 11$.	Value of harmonic component of current is between 0,2 and 6 % of Unomina l %.	Value of harmonic component of current is between 0.2 and 6 % of Unomina l %.	Maximal harmonic component of current is between 0.058–0.04 %, for odd harmonics 0.06–0.18 %
Voltage fluctuation	Voltage fluctuation on RE wires in normal working conditions should not exceed value from – 12 to +10 %.	Normal allowable voltage fluctuation is ±5 %. Allowable critical one is ±10 %.	Normal allowable voltage fluctuation is ±5 %. Allowable critical one is ±10 %.	Voltage fluctuation within power grids on RE wires is not more than 2 %.

1.2 Comparative analysis of optimization tasks for distributed power networks with RE

A number of optimization tasks for distributed power networks with RE is solved in engineering practice of different countries. They can be divided into those solved on the stages of developing and exploitation (fig. 1.3). Optimization tasks like autonomous work, disposition of commutation equipment and formation of communication network are closely interrelated and almost cannot be solved in modern conditions [38]. RE autonomous work, considering conditional controllability and instability of those energy source, is in fact impossible without a developed communication network. Availability of the last one will allow to get bilateral connection between RE and electric power consumers, according to Smart Grid concept, and regulate modes of power consumption, supporting autonomous work conditions.

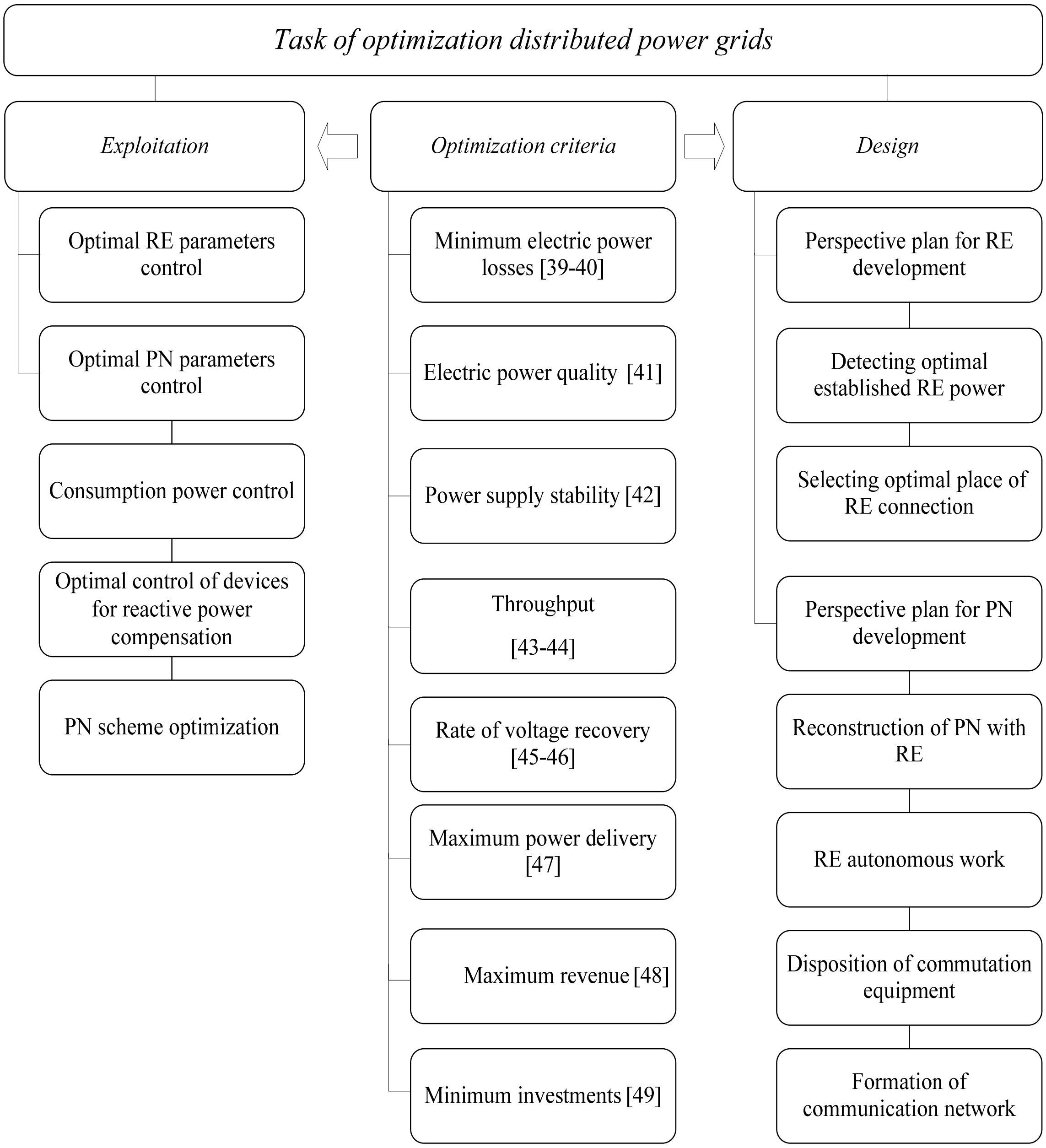

Figure 1.3 – Task of optimization of distributed power grids with RE

Usually mentioned tasks are solved by decomposing to tasks of RE functioning optimization and tasks of PN functioning. Depending on tasks in place, each of them is solved using one of the optimally criterion, such as: minimum power losses [39–40], power quality [41], power supply stability [42], transfer capacity [43–44], rate of voltage recovery [45–46], maximum of power realization [47], maximal financial returns [48], minimal investments [49] etc. Overview of optimization tasks for distributed power networks with RE is given in the attachment A.

When choosing optimally criterion and forming the appropriate mathematical model, it is worth considering that at the same time with the development of distributed generation, economic conditions of electric power functioning as a branch also change, in particular, transition to a new competitive model of wholesale power market – market of bilateral contracts and compensative power market.

In case of power supply implementation by bilateral contracts with involvement of RE, when the last delivers power to electric power grid, necessity to coordinate their work with power system that supplies centralized supply arises. This becomes mandatory when established power of RE in PN makes up a significant part of its total load (for example, 20 % and more). In this case, REN may and should be considered as a local electric system (LES), where tasks of exploring static and dynamic RE stability and other tasks typical for an electric system arise, besides the mentioned ones [38].

Among complex of tasks that arise during the process of introducing RE, it is reasonable to study and solve, first of all, those that influence directly on scales and intensity of RE development, and those that at right solving, together with “green tariffs”, will form a solid motivation for investors and power supply countries regarding RE development in Ukraine.

Such a task, in particular, is the task of getting maximum revenue from RE exploitation for their development in condition of reducing electric power losses and improving its quality in LEN, as well as increasing stability of power supply [38]. At this, considering that electric power from RE is transferred by LEN wires simultaneously with electric power of other sources, it is necessary to distinguish the part that relates to transit from RE from total power losses.

1.3 Tasks of functioning optimization of renewable energy sources in local electric systems

To research conditions of RE optimal functioning, optimization tasks (see attachment A) inherent to exploitation of such electric power sources in LES are analyzed. Basing on analysis, list of LES with RE functioning optimization tasks was adapted to specifications of their operation in Ukraine's electric power system.

1. For optimization of RE functioning in normal operating modes of electric power systems, problems of planning organization and operative control of operating modes of such stations with the aim of getting maximum revenue from their exploitation are extremely actual. So, for the present time the most actual task, considering the specifics of providing profitability of RE [50, 52], is the problem of optimizing daily modes (on time interval [t_0; t_k]) of driven energy sources $P_i(t)$, $i = 1,2\ldots n$ (for example SH) with consideration of modes of conditionally controllable sources for providing maximum revenue from implementing their electric power in conditions of multistage tariff of power market c(t) and technical restrictions from the side of separate RE [53]:

$$\int_{t_0}^{t_k} \mathrm{c}(t)\sum_{i=1}^{n} P_i(t)dt \rightarrow \max . \qquad (1.1)$$

2. In case of RE control in modes related to localization of abnormal situations in a power system, it is reasonable to pass to solving the task of RE mode optimization with the aim of decreasing the dependence of LES with cumulative load $P_{\text{load}}(t)$ from centralized power supply, i.e. minimization of LES load to main supply center $P_{\text{MSC}}(t)$ [50, 53]:

$$\int_{t_0}^{t_k} P_{\text{MSC}}(t)dt \rightarrow \min \qquad (1.2)$$

with consideration of balance restriction: $P_{\text{MSC}}(t) + \sum_{i=1}^{n} P_i(t) - P_{\text{load}}(t) = 0.$

3. To provide LES stability in the periods of maximum (minimum) consumption or limited carrying capacity of the centralized power supply system, when varying of local generation parameters may lead to breaking restrictions to ES mode parameters, optimization of RE modes is topical, as the goal is to minimize deviations from established centralized graph of cumulative generation at specified restrictions to primary power resources and RE characteristics [50, 53]:

$$\int_{t_0}^{t_k} \frac{1}{2}\left(P_{\mathrm{RE}}(t) - \sum_{i=1}^{n} P_i(t) \right)^2 dt \to \min \;. \qquad (1.3)$$

Here predictive information about meteorological parameters that is provided by a proper AUC subsystem should be considered [5].

4. To provide RE profitability, especially topical are the problems of planning organization and operative control of their operation modes with the aim to get maximum revenue from electric power realization [50, 52]. RE functioning in local electric power system is subject to particular control rules depending on situation. But applying calculus of variations methods combined with criterial method allows to get generalized optimality conditions for optimization tasks that differ just by value of parameters [50, 83].

Complex of *n* controlled RE (on example of SH) and *m* conditionally controlled wind farms (WF) and SPP is specified. The expected value of their total active power makes up:

$$M_{VAR}(t) = M_{\mathrm{WF}}\{P(t)\} + M_{\mathrm{SPP}}\{P(t)\}. \qquad (1.4)$$

It is necessary to find modes of controlled sources (small hydro) $P_i(t)$ on time interval $[t_0;\ t_k]$ that would provide maximum revenue from realization of electric power of all RE complex on electric power market:

$$\int_{t_0}^{t_k} \mathrm{c}(t)\left[\sum_{i=1}^{n} P_i(t) + M_{VAR}(t) - k_{\mathrm{c}}(t)\cdot \Delta P_{\mathrm{RE}}(t) \right] dt \to \max \;, \qquad (1.5)$$

where $k_{\text{c}}(t)$ is weight factor determined by correlation of selling tariff for RE c(t) and cost of power losses for given distribution network ц$_0$ and depends on conditions of electric power transfer contract;

$\Delta P_{\text{RE}}(t)$ – component of power losses in distribution power networks specified by RE functioning.

In the quality of restrictions, daily flows on each SH are specified $W_i - \int_{t_0}^{t_k} Q_i(t)dt = 0$, as well as the balance of flows in cascades. It is also necessary to consider inequality constraint on power of controlled RE $P_i^{\min} \le P_i(t) \le P_i^{\max}$, and also on head $H_i^{\min} \le H_i(t) \le H_i^{\max}$, herewith limit values $P_i(t_0)$ and $P_i(t_k)$ are considered to be known.

In fact, optimization task for RE in LES functioning is reduced to providing maximum electric power delivery by controlled sources, independently on power networks and conditionally controlled RE work modes [50]:

$$\int_{t_0}^{t_k} \text{c}(t) k_{\text{tr}} \sum_{i=1}^{n} P_i(t)dt \to \max \,, \tag{1.6}$$

where k_{tr} is the factor that considers revenue diminution for RE due to compensation of losses to transporting electric power by networks.

Analysis of conditions of optimal functioning modes in local electric power renewable sources showed that to reduce electric power losses and improve its quality indicators it is reasonable passing to solving of complex LES scheme optimization task, which provides for implementation of efficient project solutions and introducing systems for operative reconfigurations of RE connection schemes.

1.4 Research of methods for optimization renewable energy sources functioning in local electric systems

1.4.1 Optimal reconfiguration of local electric system

As it happens that LES is loaded irregularly, it needs correction of power flow that may be executed by proper grid reconfiguration. Reconfiguration is the process of changing LES configuration by changing the position of commutation devices, changing at the same time network

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