Anticipatory control of transit power flows from the renewable energy sources in electric power system

Volodymyr Kulyk
dept. of Electrical Stations and Systems
Vinnitsa National Technical University)
Vinnitsa, Ukraine
volodymyrvkulyk@gmail.com

Olexander Burykin
dept. of Electrical Stations and Systems
Vinnitsa National Technical University)
Vinnitsa, Ukraine
mr.burykin@gmail.com

Juliya Malogulko
dept. of Electrical Stations and Systems
Vinnitsa National Technical University)
Vinnitsa, Ukraine
juliya_malogulko@ukr.net

Vladyslav Hrynyk
dept. of Electrical Stations and Systems
Vinnitsa National Technical University)
Vinnitsa, Ukraine
vladgreen14@gmail.com

Abstract — **An anticipatory control method for optimizing transit power flows in the electrical power system (EPS) caused by renewable energy sources (RES) is proposed. For the organization of control, the forecasted RES generation schedules obtained on the base of retrospective data and forecast meteorological parameters are used. It is proposed to use the algorithm of the electric grid state estimation on the basis of the method of least squares in order to reconcile the forecasted schedules of electricity input and output within the information window of control. It is proposed to determine the power losses from the transit flows of RES for individual time slice by the method of overlapping with the preliminary linearization of the steady-state EPS model. This approach makes it possible to detect electricity transactions from RES in certain lines and intersections, to identify strong links between the generation of such sources and the optimal parameters of the EPS regulators. This improves the accuracy of short-term forecasting of EPS mode parameters and the adequacy of the formation of control effects for transit power flows optimization based on the minimum power loss criterion.**

Keywords — electric power system, renewable energy, anticipatory control, transit power flows, state estimation.

I. INTRODUCTION

The development of renewable energy in Ukraine is supported at the national level in the National Renewable Energy Plan for the period up to 2020 and the Energy Strategy of Ukraine for the period until 2030. According to the documents for the period until 2035, the share of renewable energy sources (RES) in the overall structure of energy consumption in the country should be 35%.

Thanks to state support for the development of renewable energy sources, installed capacity of wind and solar power plants reached 3136 MW in the first quarter of 2019, and 862 MW of them was put into operation in 2019.

Keeping this trend in the future in the absence of control over the geographical location of RES generation impartially necessitates the need to increase the flexibility requirements of the traditional power generating units of Ukrainian united energy system (UES) and additional network construction to ensure operational security during certain periods of the day, particularly during maximum insolation.

Additional networking to support the integration of RES through increased network capacity will allow new sources to be connected. Increasing the share of RES will require new measures to ensure an operational balance in the grid. The electrical power system (EPS) is already experiencing a shortage of shunting power. This is due to the high base capacity of nuclear power plants. Increasing the installed capacity of RES not only does not contribute to the flexibility of the EPS, but also creates new challenges.

It is possible to eliminate the shortage of reserves and improve the balance in the grid by building energy storage systems and developing demand management systems. An effective supplement to these solutions, which will delay their implementation, is to improve the day-to-day operational planning of the advance transmission system. For the purposes of such planning, forecast schedules of load, power transits and RES generation, obtained using retrospective data and forecast meteorological parameters, may be used.

Operational planning consists in the development of the necessary technical measures and actions of the relevant personnel of the transmission system operator (TSO) to ensure the ability of the grid to meet the total demand for electricity and power at any given time, in compliance with the established quality and reliability parameters of these services [1].

Intra-day operational planning should support the operational security of the EPS. However, the interference of TSO dispatchers in RES power is only allowed if there is a real or foreseeable threat of reliability breach of the operation mode of the backbone or distribution networks [2].

Thus, the increasing impact of RES generation limits the ability of the TSO dispatcher to balance power issues. On this basis, there is a problem of improving the means of daily correction of internal and transit flows in the EPS, in particular from RES. Appropriate mathematical software for advanced estimation of the EPS mode parameters will allow the TSO manager to make reasoned decisions regarding the correction of the backbone electrical grid load by redistributing transit flows from RES via operational controls.

Traditionally, numerical methods of linear and nonlinear programming have been used to implement approaches to the control of EPS transit power flows and to select optimal technical solutions [3-7].

Power system models have been developed and simulated in the literature in order to study the effect of increasing penetration of RES cross-border flow. Such models are simulated in [3] in order to study the congestion of individual interconnections in different scenarios of wind power penetration in Europe.

In [4] proposed a three-level model for optimal transmission considering uncertainty in demand and renewable energy. In [5] proposed a robust coordinated transmission and generation planning model with a novel uncertainty representation approach of the net load with high penetration of RES.

In [6], [7] analyzed the impact of wind power variability on generation planning and analyzed the impact of operational flexibility on generation planning with renewable target.

A common drawback of these is that they provide partial solutions that are significantly dependent on the initial approximation and dimension of the optimization problem. In this paper finding the best solution does not begin with the initial approximation by sorting through options, but with the ideal state by imposing constraints on the parameters. Based on this, the proposed combination of methods, algorithms and means of optimizing the transit flows from RES allow to provide the lowest possible energy consumption with the quality assurance of electricity.

II. ESTIMATION OF EPS MODE PARAMETERS USING THE FORECASTED RES GENERATION SCHEDULES

The problem of EPS mode parameters estimation can be considered as a problem of minimizing the errors of measurement of the mode parameters in the state estimate theory (SET) of the EPS [8-12]. Several approaches have been developed to analyse the reliability of the information being measured. The classic SET problem of power engineering [11] uses state equations as the equations of steady state in the form of power balance. Currents, voltages, flows of active and reactive power are considered telemetries with a given probability [8]. The EPS mode, characterized by these parameters, corresponds to a certain moment (interval) of time and is constantly changing. Therefore, it is necessary to adjust the telemetry periodically so that, in combination with the probable mode parameters, they obey power balance in the EPS.

In the case of an advance estimation of EPS regime parameters for predicted daily correction of transit flows from RES, the estimated values of RES generation and power consumption are used as pseudo instrumentation. It is advisable to use a state estimation algorithm [12] to reconcile the predictable values of electricity input and output within the information "window". The SET method based on the least squares method is based on the linearization of the relationship between the pseudo instrumentation and the state variables of the electrical network. The nonlinear relationships between the state vector and the measured electrical variables can be reported as [12]:

$$\mathbf{z} = \mathbf{h}(\mathbf{x}) + \mathbf{v}, \tag{1}$$

where **z** – the vector of measured parameters of electrical networks (EN) (pseudo instrumentation); x – the vector of the EN state variables; **h(x)** – a vector function that relates measurements to state variables based on the equilibrium equations for EN; **v** – the vector of deviations between the measured and calculated mode parameters.

An infinite number of combinations of variable values can be used to form the vector of state **x**, however, a combination that minimizes the absolute values of the vector **v** is of practical value. Based on this, the objective function of the problem of determining the vector state EN in the general form is:

$$\begin{aligned} J(x) &= \sum_{i=1}^{m} \frac{\left[z_i - h_i(x)\right]^2}{\sigma_i^2} = \\ &= \left[z - h(x)\right]^T W \left[z - h(x)\right] \to \min, \end{aligned} \tag{2}$$

where σ – a standard deviation of each measurement; $W = diag\left[\sigma_1^2, \sigma_2^2, \ldots, \sigma_m^2\right]^{-1}$ – inverse diagonal matrix of the expected (estimated) root-mean-square deviations of individual measurements.

A feature of backbone electrical networks is the sufficiency of the observation vector **z**. That is, using only measured parameters, the state of the EPS can be identified with high accuracy. However, the advanced observation and control of the probable modes of the electric network within one or two half-hour intervals necessitates the need to supplement the vector **z** with the power values from the predicted (claimed) RES generation schedules [13].

For the implementation of optimal solutions for the control of power flows and voltages in the EPS autotransformers with longitudinal and transverse regulation can be used, which requires the determination of their optimal transformation coefficients by the criterion of the minimum loss of active power.

III. DETERMINATION OF CONTROL EFFECTS FOR OPTIMIZATION OF RES TRANSIT CAPACITIES BY THE CRITERION OF THE MINIMUM OF LOSSES OF ELECTRICITY

The task of optimal control of transit power flows is to adjust the current transformation coefficients of the regulating devices in order to introduce in the closed contours additional unbalanced e.m.f. that approximate the flow distribution to the optimum [14].

As you know, unbalanced e.m.f. in relative units is determined by the product of the transformation ratios that are included in the circuit, considering the direction of its bypass [13]:

$$\dot{\mathbf{E}}_{unb*} = 1 - \prod \dot{k} . \qquad (3)$$

where $\dot{\mathbf{E}}_{unb*} = \dot{\mathbf{E}}_{unb} \cdot U_b^{-1}$; $\dot{k}$ is the vector of the products of transformation ratios that are included in the circuit, considering the direction of its bypass.

To ensure the unambiguity of transit flows optimization problem in the EPS [14, 15], the number of regulated transformers is assumed equal to the number of circuits, that is, the remaining transformers included in the circuit are unchanged. Then each element of expression (4) is defined as:

$$\dot{\mathbf{E}}_{unb*d} = 1 - \prod_{d} \dot{k}^{tr} \cdot \dot{k}_d^{chor} . \qquad (4)$$

where $\dot{k}_d^{chor}$ is the transformation coefficient of the regulated transformer, which are in the chord of the d-th loop of the circuit; $\prod_{d} \dot{k}^{tr}$ – product of unchanged transformation coefficients of transformers of the d-th loop of the equivalent circuit that are included in the graph tree.

According to [11], expression (4), as a function of time, is:

$$\begin{aligned} \dot{k}^{chor}(t) &= \dot{k}_{diag}^{tr\;-1} \cdot n_t + \\ &+ \alpha \cdot \frac{1}{\sqrt{3}} \overline{\mathbf{S}}_D(t) \cdot \overline{\mathbf{U}}_D^{-1}(t) \cdot n_t \cdot U_{б}^{-1}(t) \end{aligned} \qquad (5)$$

where $\dot{k}^{chor}$ is the vector column of the transform coefficients of the adjustable transformers, which are the chords of the contours of the circuit diagram; $\dot{k}_{diag}^{tr}$ – diagonal matrix, each element of which is the product of transformation coefficients of transformers, which are included in the corresponding circuit and belong to the tree branches of the graph; n_t – single transposed vector-line; $\boldsymbol{\alpha}$ – matrix of influence coefficients; $\dot{\mathbf{U}}_D$ – diagonal matrix of node voltages; $\dot{\mathbf{S}}_D$ – diagonal matrix of capacities in nodes.

In [15], the matrix of influence coefficients is determined by the expression:

$$\boldsymbol{\alpha} = \dot{k}_{diag}^{tr\;-1} \cdot \dot{\mathbf{N}}_{k\,bal} \cdot \dot{\mathbf{z}}_{в} \cdot \dot{\mathbf{C}}_e . \qquad (6)$$

where $\dot{\mathbf{N}}_{k\,bal}$ is the matrix of branch connections in the circuits of the equivalent EPS network taking into account complex balanced transformation coefficients, which, unlike the matrix of branch connections in the circuits of the network **N** for the branches that are included in the i-th circuit, contains the products of the transformer transformation coefficients in the direction bypassing this circuit [16]; $\dot{\mathbf{z}}_{в}$ – diagonal matrix of resistance of branches; $\dot{\mathbf{C}}_e$ – is the matrix of current distribution coefficients for the equivalent r-scheme.

The elements of the matrix $\boldsymbol{\alpha}$ have the content of influence coefficient of the power of the nodes on optimal transformation ratios of the transformers. The specified influence coefficients are unchanged and do not depend on the parameters of the mode, under the conditions given in [14, 15]. Therefore, the influence coefficients $\boldsymbol{\alpha}$ characterizing the effect of the change in the injection currents on the optimal transformation ratios can be used to analyse their sensitivity to the change in the predicted RES generation power.

So,

IV. OPTIMIZATION OF RES CAPACITY ALLOCATION BASED ON OPERATIONAL PLANNING AND ANTICIPATORY CONTROL

Whereas the dynamic nature of the EPS and the low adequacy of forecasting RES capacities, which correspond to the decision-making interval of control, the results of operational planning need constant correction.

Reducing the forecasting period of the variable EPS mode parameters usually contributes to the adequacy of the forecast. Therefore, the use of forecast data within one or two half-hour intervals allows to improve the results of short-term optimization of the EPS modes and to adjust the parameters of the control devices. The justified limitation of the number of control effects within the information "window" helps to increase the stability of the control process and the economical use of the resource of control devices.

To illustrate the proposed approach to optimize the transits of RES power by adjusting the transformer transformation ratios, a subnetwork of the 110-330 kV circuit (Fig. 1) of the South-western Electric Power System (SEPS) of Ukraine was used.

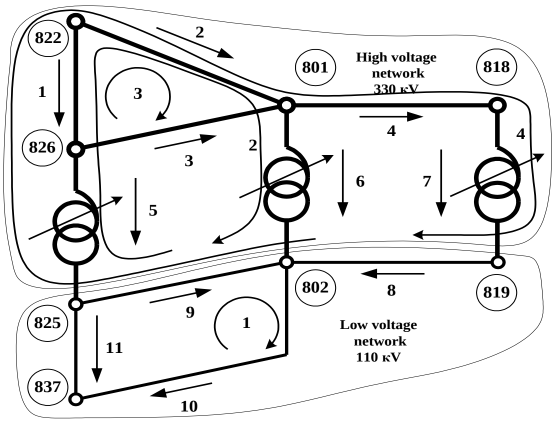

Fig. 1. Scheme fragment 110-330 kV of SEPS

For the reproduction of the EPS modes, the forecast load diagram of consumers and the generation of RES transmitting energy to the buses 819 were used. The total load of the buses 819 and the graph of the change in the total RES power are presented in Fig. 2. Due to the considerable installed capacity of solar power plants, the power fluxes on the 819 buses vary widely, and in the time interval from 10:00 to 14:00 change their direction.

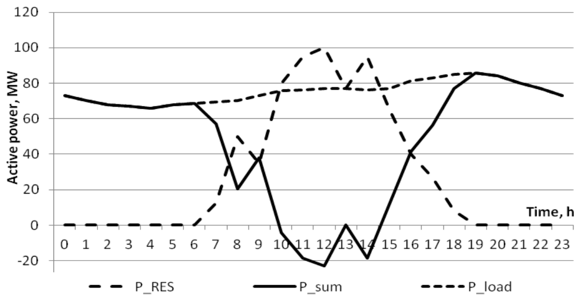

Fig. 2. Diagrams of load (P_{load}), generation of RES (P_{RES}) and summary electricity demand at 819 bus

Using the expressions (5) and (6) for each time interval of the load diagram (Fig. 2), the transformation coefficients of the transformer 818-819 were determined, which correspond to the minimum electric loss from the transportation of RES power (Fig. 3). Energy loss saving is achieved by redistribution of load between the 330 kV and 110 kV grids according to the change of load and RES generation.

The results of the calculation show that the cross-regulation means are more efficient in order to optimize the transit of power from RES. In order to realize the optimal mode of fragmentation of the EPS in terms of power losses, it is necessary to execute 12 control effects with the help of phase-shifting transformers (PST) 818-819 and to perform 20 changing of the taps (Fig. 4a). This will reduce electricity losses by about 8% during the day.

The optimal PST parameters have a higher sensitivity to active power flows in the power system. This is evidenced by frequent changes in state of the PST in adjacent time intervals. Therefore, in order to ensure the adequacy and stability of the control in such conditions, it is necessary to consider the dynamics of load and generation changes within the control information window.

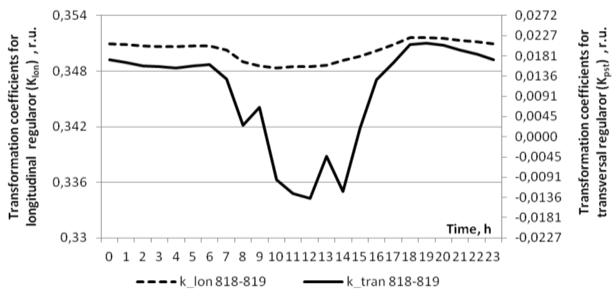

Fig. 3. Diagram of transformation ratios of transformer 818-819 with longitudinal (K_{lon}) and transversal (K_{tran}) regulation (PST)

In order to assess the need for each individual control action, it is necessary to consider not only the current parameters of the mode provided by the facilities of the operational information complex, but also their predicted values for the next control interval.

The decision to operate a transformer must be based on a comparison of the effects of reducing the losses and risks associated with the use of the control unit resource and changing the operation of the transformer. If during the adjacent time intervals (Fig. 4a) it is necessary to execute several control actions in one direction (7:00 and 8:00), and even more so in opposite directions (8:00 and 9:00), then appropriateness of such control is usually not confirmed [17].

Thus, it is possible to propose an algorithm for implementing the proposed approach.

1. Calculation of the matrix of influence undependable from the parameters of the EPS mode by expression (5). (Once for the power scheme);
2. Balanced vector of x state by EPS steady state estimation procedure (1), (2) forming. The results of short-term forecasting of RES generation and loading within one to two half-hour intervals are used for such assessment;
3. Optimal transformation ratios of the transformers by minimal power loss criterion calculation for the next control interval by expression (6);
4. If the calculation results indicate the need for control effects with one device in the current and subsequent time intervals, then the current control influence is ignored, otherwise optimal parameters of the control devices for the next control interval is applied.

Using the described algorithm, a schedule for changing the positions of the switch PST 818-819 was formed (Fig. 4b).

Comparison of the switching schedules of PST 818-819 (Fig. 4) shows that considering the results of the real-time forecast made it possible to significantly reduce the number of control actions (6 instead of 12) and the number of switches (12 instead of 20). The implementation of such a control circuit is associated with some increase in power losses, compared to optimal ones. The losses increased by 0.2%. However, the average effectiveness of one control actions has almost doubled, indicating the high efficiency of the proposed approach.

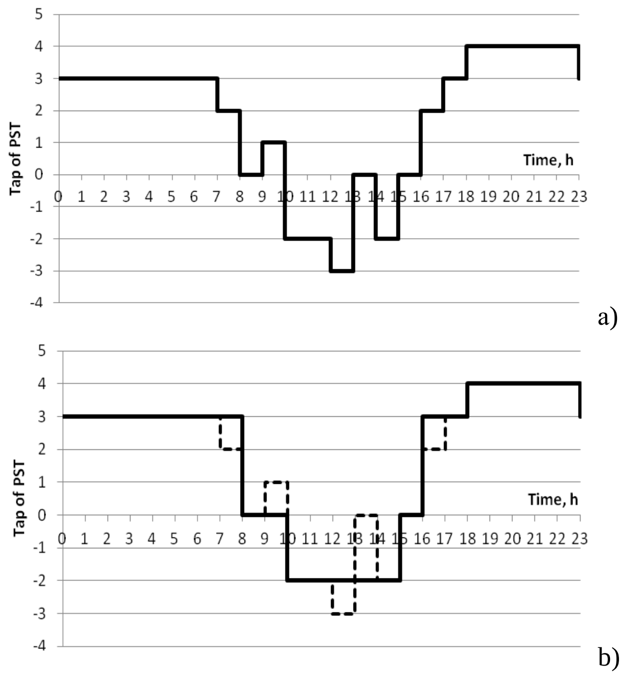

Fig. 4. Diagram of the switch position change of the phase-shifting transformer 818-819 without taking into account the anticipatory control (a) and with its consideration (b)

V. CONCLUSIONS

1. The increase in RES installed capacity objectively necessitates the need to increase the flexibility requirements of the traditional Ukrainian power generating facilities and additional network construction to ensure operational security. The intervention of TSO dispatchers in the production of RES power is only allowed if there is a real or foreseeable threat of disruption of the backbone grids. Therefore, an effective means of ensuring the continuous operation of the EPS is the organization of day-to-day operational planning of the modes of the transmission system with anticipatory control.

2. Taking into consideration the dynamic nature of the EPS and the low adequacy of forecasting RES capacity, the results of operational planning need constant updating. The use of predicted data within one or two half-hour intervals allows to define the results of short-term optimization of EPS modes more accurately and to adjust the parameters of control devices. Considering the results of the real-time forecast can significantly reduce the number of control actions and the number of switches. The reasonable limitation of the number of control actions within the information "window" helps to increase the stability of the control process and the economical use of the service life of control devices.

3. In the case of an advance estimation of the parameters of the EPS regime for the daily correction of transit flows from RES, it is advisable to use the predicted values of RES generation and electricity consumption. In order to reconcile the predicted values of electricity input and output within the information "window", state estimation algorithms must be used.

4. The application of the developed model based on the matrix of influence coefficients will allow determining the optimal transformation coefficients with the minimum number of calculations. The use of the proposed approach to optimize the flux-distribution by minimum power losses criterion allows determining the most favourable control power flows from RES due to the possibility of realizing the optimal flow distribution by the available electricity distribution control devices.

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