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Algorithm of voltage and reactive power regulation based on the particle swarm method

***Abstract**. In this paper the results of the development of voltage and reactive power regulation algorithm based on the particle swarm method, optimizing the electric power system mode by the level of losses, are presented. To provide an integration of this algorithm into a real system of an automated dispatching control system, the algorithm is implemented using programs, which are used in the System Operator of the Unified Power System of Russia, as well as standard communication protocols and a software platform. The analysis and comparison of the optimization results obtained by the particle swarm method and standard optimization method (gradient descent method), realized in RastrWin, confirm the correctness and reliability of the obtained results and the developed algorithm. At the same time, the algorithm does not depend on the initial conditions (setpoints), set on the control objects, which allows it to be used to optimize the modes of complex power network, finding the balance in which is a time-consuming task. In the future, it is planned to develop an algorithm for optimizing the mode, taking into account the increased stability of the electric power system.*

Streszczenie**. W artykule przedstawiono metodę sterowania napięciem I moca bierną bazującą na algorytmach rojowych. Algorytm zaadaptowano do rzeczywistych warunków sieci dystrybucyjnej w Rosji. Sprawdzono praće algorytmu badając stabilność I niezawodność systemu. W dalszym etapie planuje się zastosowanie metody do optymalizacji sieci zasilania. **Metoda sterowania mocą bierną bzazująca na algorytmach rojowych

Streszczenie. **Keywords:** electric power system, voltage and reactive power regulation, algorithm, particle swarm method.
Słowa kluczowe: sterowanie moca bierna I napiuęciem w sieci zasilającej, algorytmy genetyczne..

Introduction

Currently with the introduction of distributed generation, the problem of optimal voltage and reactive power regulation is one of the most important tasks in studying and controlling of electric power system (EPS) modes [1, 2]. The problem of optimization of EPS modes in general terms is to determine the steady state mode (in particular, the combination of the voltages at the nodes and corresponding reactive power flows) that corresponds to the minimum value of total active power losses. Due to the fact that the operation of voltage regulation is carried out both in normal, emergency and post-accident modes of EPS, it should be considered and implemented not only at the design stage, forecasting of load and generation schedules, but also in the current operation mode – with the help of local and centralized operational dispatching or automatic control systems. This determines the need for consistent collection of operational data of EPS and transmitting of control actions (CA) to the relevant controlled objects (CO).

One of the key aspects in automation of regulating process is the development of an effective control algorithm, based on which the relevant data would be formed. At the same time, this algorithm should be able to be integrated into the existing SCADA (Supervisory Control And Data Acquisition) system to ensure information interaction with the CO and the EPS as a whole.

Traditionally, methods of the modal analysis [3], the sensitivity analysis [4], the analysis of power flows EPS [5] and voltage stability indices [6] are used for the voltage stability analysis. However, these methods are not suitable for estimating voltage stability in the EPS due to time-consuming and computational requirements. In recent years, there are works that present the results of building intelligent control systems using elements of evolutionary modeling to accelerate the task of determining the optimal mode for reactive power in the EPS [7, 8]. In particular, devoted to the development of algorithms for voltage and reactive power regulating based on fuzzy dynamic programming, evolutionary programming, genetic algorithm are presented in [9, 10, 11]

This article presents the results of the development and implementation of an algorithm for voltage and reactive power regulation in the EPS, optimizing the mode by the level of losses, based on the particle swarm method. In this case, the transformers and reactive power compensation technologies (VAR compensators) are used as controlled objects (CO).

Algorithm description

The particle swarm algorithm was proposed in 1995 by James Kennedy and Russell Eberhart [12]. The idea of the algorithm was partly borrowed from studies of the behavior of clusters of animals (shoals of fish, flocks of birds, etc.), the model was slightly simplified and elements of the behavior of crowds of people were added, so, unlike, for example, the algorithm of bees (Artificial Bee Colony Algorithm and Bees Algorithm) [13, 14] the agents of the algorithm (possible solutions) were called neutral – particles.

Figure 1 shows a block diagram of the particle swarm algorithm. For example, there is an n-dimensional space (search area) in which the particles (agents of the algorithm) are located. At the beginning, the particles are scattered randomly throughout the search area and the state of each particle is characterized by coordinates in the solution space, as well as the velocity vector of the movement. At each passed point that the particle has passed, the value of the objective function and the fixation of the position (set of variables) in which the best solution was found are calculated. In this case, each particle remembers what (and where) the best value of the objective function it personally found, and each particle knows where the point is located, which is the best among all the points that all the particles have passed (globally the best solution).

At each iteration, the particles adjust their velocity (modulus and direction) to be on the one hand closer to the best point that the particle has found itself (the authors of the algorithm called this aspect of behavior "nostalgia"), and, at the same time, closer to the point that is currently globally best. After a certain number of iterations, the particles should gather near the best point, although it is possible that some of the particles will remain somewhere in a relatively good local extremum, but the main thing is that at least one particle is near the global extremum.

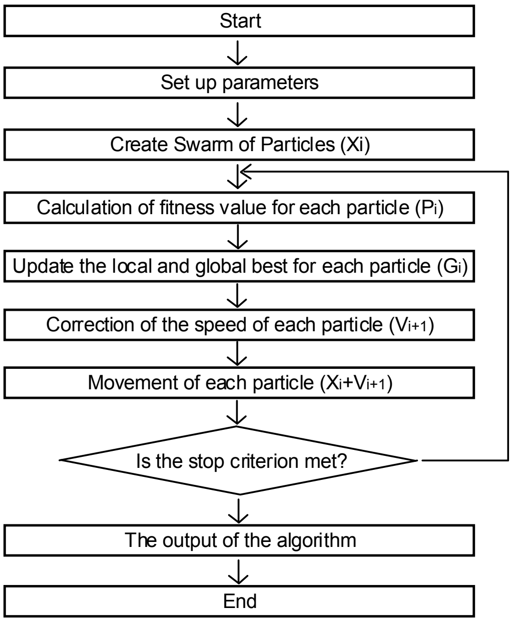

Fig.1. Flowchart of Particle Swarm Optimization

The algorithm is integrated into the existing structure of the automated dispatching control system in accordance with the block diagram in figure 2.

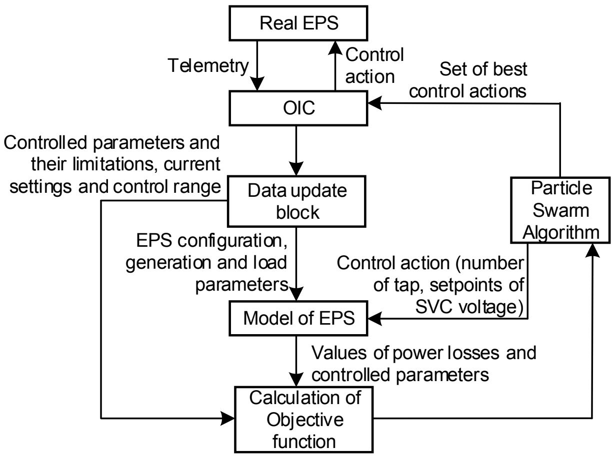

Fig.2. Block diagram of the proposed voltage and reactive power control system

On the basis of the current data on the EPS received by the Operational and informational software complex (OIC), the analysis of the scheme-mode situation and subsequent updating (Data update block) of the calculation model of the EPS (implemented in the RastrWin software package [15]) and the formation of initial data for the implementation of the particle swarm algorithm (in particular, the values of controlled parameters, reactive power reserves in the EPS, current setpoints of equipment involved in voltage and reactive power management, the list of equipment that is available for remote control and other equipment under the control of the dispatching service, transformation coefficients of power transformers).

In the mode of optimization loop, the RastrWin-AstraLib.dll library was used to calculate the steady-state mode of the EPS. Communication between RastrWin and the particle swarm method was carried out by the Microsoft Visual Studio development environment on the .NET Framework 4.5 software platform (C# language).

Calculation of new CA (v_{i+1}) occurs in accordance with the formula:

(1) $$v_{i+1} = v_i + a_1 \cdot rnd_1() \cdot (\mathrm{p}_i - x_i) + a_2 \cdot rnd_2() \cdot (\mathrm{g}_i - x_i)$$

where: v_i – the component of the velocity at iteration; x_i – the coordinate of a particle in solution space; p_i – coordinate of the best solution of the particle (local optimum); g_i – coordinate of the best solution in the whole swarm (global optimum); $rnd_1()$ и $rnd_2()$ – random numbers in the interval (0;1); a_1, a_2 – weighting factor.

The objective function (F) is calculated as the sum of the losses and penalty values, which are used to limit the controlled parameters (voltages in the nodes and currents of the equipment):

(2) $$F = \Delta P + \Sigma(k_I \cdot \Delta I_i) + \Sigma(k_Q \cdot \Delta Q_i) + \Sigma(k_U \cdot \Delta U_i)$$

where: k_I, k_Q, k_U – penalty coefficients for current, reactive power and voltage, respectively; ΔI_i, ΔQ_i, ΔU_i – the values of current, reactive power and voltage deviations from the permissible values (contained in the steady-state calculation model) correspond to the requirements; ΔP – network power losses.

The value of power losses (ΔP) can be calculated as:

(3) $$\Delta P = \sum P_{Gi} - \sum P_{Li}$$

where: $\sum P_{Gi}$ - total generators' production (it can be expressed as sum of total generated power of each generator unit in the network and net interchange power (total power flow from external system); $\sum P_{Li}$ - total consumers' load.

If the stop criterion is met, the calculated set of optimal effects is transmitted via IEC 60870-104 to the OIC, where it can be implemented in the presence of remote control channels and the possibility of their use.

The algorithm can determine the following CA: voltage/reactive power setpoints of generators and smoothly regulated VAR compensator; status of circuit breakers of switched discretely controlled VAR compensator; number of tap (On-Load Tap Changer (OLTC)) of transformers and thyristor-controlled booster transformers. The algorithm can form the optimal CA as recommended for the operational personnel of the dispatching center, if part of the objects is not opened for remote control and requires the participation of the operational personnel of the power station or substation.

Taking into account the presence of VAR compensator, the complexity of the scheme and the nonlinearity of the load, the function of active power losses in the EPS has many local minima, so finding a global minimum is a random event. In order to obtain a result at least not worse than the existing one for the same scheme-mode situation, and to increase the probability of finding the global minimum, when creating a swarm of particles, a part of the particles is not formed randomly, but is selected from the database of the best coordinates of the particles obtained in the past.

Preparing data for the algorithm

The test model of the EPS is implemented in the RastrWin [15] software package and is presented in figure 3. RastrWin is a program used by the System operator of the Unified Power System of Russia.

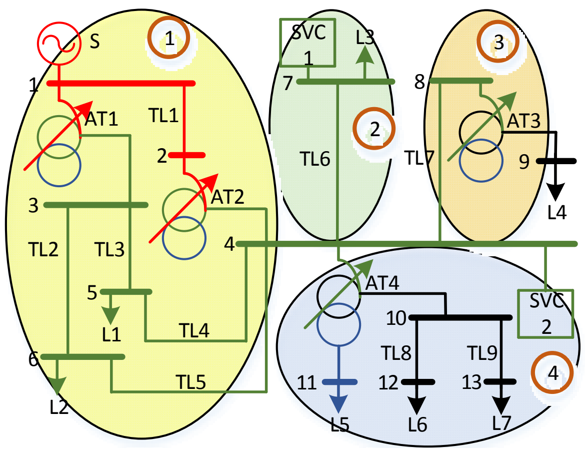

Fig.3. EPS test circuit, AT – autotransformer, TL – transmition line, L – load, SVC – Static Var Compensation, S – external system

In the analysis, it is considered that all the equipment is opened under remote control. The circuit of the electric network contains a section of the network with parallel connections at different voltage classes, the flow between which can be controlled by changing the tap of the on-load tap changing transformers (AT1 and AT2). Transformers AT3 and AT4 are also equipped with on-load tap changing devices, which allows to optimize losses in distribution networks. Two static thyristor compensators (Static Var Compensation (SVC)) are installed as VAR compensator at substations 4 and 7. In accordance with the specified static characteristics the loads do not depend on the mains voltage. For convenience of the analysis of results the scheme is divided into 4 power districts, in which it is quite easy to allocate the most influencing SVC.

The parameters of the EPS test model are given in table 1 and 2.

Table 1. Simulation parameters (initial data on nodes)

№	U_{nom}, kV	P_L, MW	Q_L, Mvar	U_{set}, kV	P_G, MW	Q_G, Mvar ($Q_{G\min}...Q_{G\max}$)
1	500			500	400,7	-202,4
2	500					
3	220					
4	220			225		-125,5 (-150…250)
5	220	30	20			
6	220	25	15			
7	220	150	154,9	220		153,3 (-150…250)
8	220					
9	110	130	90			
10	110					
11	11	15	9,3			
12	110	20	15			
13	110	14	12			

The algorithm is tested by comparing the optimization results obtained by the proposed algorithm for an identical model (figure 3) with the results of the built-in optimization function in the RastrWin based on the gradient descent method. The results of steady-state mode calculation for the optimal regime of the EPS by the particle swarm method and gradient descent are presented in tables 3 and 4, respectively.

The particle swarm algorithm searched the required value of CA for the SVC and OLTC of transformers. The optimization cycle calculation consisted of 20 iterations, dimension of 100 particles. The value of power losses and CA of both algorithms are presented in tables 5 and 6, respectively.

Table 2. Simulation parameters (initial data on branches)

№	R, Ohm	X, Ohm	B, μS	$I_{\max}$, A
1-2	9,9	93	-1191	370
3-5	11,8	43,5	-260,4	185
3-6	23,6	87	-520,8	163
4-5	23,6	87	-520,8	122
4-6	11,8	43,5	-260,4	95
4-7	20,06	73,95	-442,7	202
4-8	20,06	73,95	-442,7	202
10-12	10,2	21	-135,4	129
10-13	10,2	21	-135,4	129

Table 3. Data on nodes after particle swarm optimization

№	U_{nom}, kV	U_{meas}, kV	δ, °	U_{set}, kV	P_G, MW	Q_G, Mvar
1	500	500	-24,29	500	400,5	-184,9
2	500	500,89	-29,92			
3	220	235,96	-26,43			
4	220	229,2	-33,99	229,2		-150
5	220	232,34	-29,81			
6	220	231,34	-32,25			
7	220	223,25	-40,31	223,3		141,6
8	220	233,74	-39,2			
9	110	116,94	-42,91			
10	110	120,9	-35,38			
11	11	10,3	-36,15			
12	110	117,49	-36,49			
13	110	118,59	-36,1			

Table 4. Data on nodes after mode optimization by gradient descent method

№	U_{nom}, kV	U_{meas}, kV	δ, °	U_{set}, kV	P_G, MW	Q_G, Mvar
1	500	500	-24,29	500	400,5	-193,3
2	500	502,38	-29,94			
3	220	234,98	-26,41			
4	220	229,15	-33,99	229,1		-150
5	220	231,4	-29,81			
6	220	230,49	-32,25			
7	220	224,12	-40,43	224,1		151,4
8	220	232,77	-39,23			
9	110	104,65	-42,87			
10	110	119,75	-35,4			
11	11	10,27	-36,17			
12	110	115,39	-36,54			
13	110	116,52	-36,14			

Table 5. Results of optimization

Power district	Particle swarm method	Gradient descent method	Δ, MW
№	ΔP, MW	ΔP, MW	
1	4,514	4,580	-0,066
2	7,510	7,500	0,010
3	3,720	3,720	0,000
4	0,675	0,720	-0,045
$\Sigma(\Delta P)$, MW	16,419	16,520	-0,101

Table 6. Set of best control actions

Power district	Control object	Particle swarm method	Gradient descent method
№		Control action	
1	SVC1, U_{set}	220,77 kV	223,12 kV

2	SVC2, U_{set}	221,38 kV	230,00 kV
	AT1, k_{OLTC}	0,476 p.u.	0,476 p.u.
	AT2, k_{OLTC}	0,474 p.u..	0,468 p.u.
3	AT3, k_{OLTC}	0,560 p.u.	0,472 p.u.
4	AT4, k_{OLTC}	0,548 p.u.	0,532 p.u.

The results of the analysis and conclusions

As can be seen, the voltage levels are within acceptable limits for both optimization methods, which indicates the correct operation of the algorithm. In addition, during the optimization process, there was an exit beyond the permissible value of the controlled value, followed by entry into the permissible region. As a result of the optimization, it was revealed that the proposed particle swarm algorithm for optimizing the mode by the level of power losses showed correct results (confirmed by similarity with the result of optimization by the gradient descent method). It is confirmed that the power losses function is not smooth at all and has a certain number of local minima. During the optimization of the scheme by the particle swarm method, the results obtained may differ qualitatively from each other. This is due to the set of extremes of the objective function (active power losses) and the fact that at the stage of swarm creating the individuals are located in the space of solutions randomly. Based on the above, we can conclude that it is necessary to optimize the scheme by swarming particles in several cycles. On the one hand, this increases the time spent on the calculation, on the other-makes it possible to find the global minimum of the objective function with a greater probability. In other words, in the process of real-time control with constant loads, generation and external flows, active power losses will decrease from iteration to iteration, ideally reaching a global minimum. In addition, the operation of the particle swarm algorithm does not depend on the initial conditions (settings) set on the CO, which allows it to be used to optimize the modes of complex schemes, finding the balance in which is a time-consuming task. The optimization time by gradient descent was around 30 seconds. While it takes 46 seconds by the particle swarm algorithm, the determining the optimum - the minimum of the objective function, is carried out in 10 seconds. However, in the future, to reduce the time, you can apply the procedure of parallelization of the optimization process, as well as optimize the work of the optimization program with the RastrWin – AstraLib library.dll.

Conclusion

The algorithm of optimization of voltage and reactive power regulation in the EPS based on the method of a swarm of particles is developed. Formed CA allowed to obtain the most optimal mode of the EPS with minimal level of active power losses. Based on the comparison of the obtained data with the optimization results obtained by the gradient descent method, it is possible to speak about the correctness and reliability of the obtained results. At the same time, the developed particle swarm algorithm does not depend on the initial conditions (setpoints), set on the CO, which allows it to be used to optimize the modes of complex schemes, finding the balance in which is a time-consuming task. In the future, it is planned to develop an algorithm for optimizing the mode, taking into account the increased stability of the EPS.

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