An Optimization Model for Determining the Optimal Voltage Regime in Industrial Electric Power Supply Systems

D. Bibev[1], D. Pachamanova[2], A. Pachamanov[3]

Abstract – **We solve for the optimal voltage regime in an industrial electric supply power system (ESPS) of the self-service consumer department of a thermo-electric power plant in real time. The objective is to minimize the total electric power of the consumers given hourly constraints on the power factor. The decision variables are the level of the supply voltage at the entrance of the main adjustable transformer substation (MATS) and the magnitude of the assigned electric loads in the ESPS. The constraints are the allowable ranges for the voltages at the terminals of the consumers and the maximum available reactive compensating electric power.**

Keywords – **Electric Power Supply, Voltage Optimization**

I. Introduction

When the terminals of consumers of electric power are fed nominal voltage, they work under their optimal regime. The deviation of the voltages from their nominal values for the nodes with assigned electric loads (consumers of electric energy) is restricted according to the requirements of the electric equipment – lighting installations, electric motion devices, technological processes. Finding an optimal regime of the voltages in an ESPS is a complex task that is solved using state-of-the-art measuring, transfer, and processing devices. After processing the operating information, actions on the ESPS devices are undertaken [1,2]. The dynamics of the active loads in an ESPS requires the voltage regime to be determined in real time through periodic control of the loading of the transformer substation and of the high-voltage motors that set in motion powerful machines (compressors, pumps, fans). The stable operating regimes can be described by a system of linear algebraic equations that are determined from the substitute circuit of the ESPS. The matrix method [3] is the most appropriate for solving for the stable voltageregimes when the supply voltage at the entrance of the MATS is given and the assigned electric loads can be measured in real time. The appropriate position of the voltage regulator of the MATS and the distribution of the compensating devices for reactive electric power are obtained by solving an optimization problem every one (or half) hour.

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II. Essence of the Problem

A. Characteristics of the ESPS

The main requirements of the voltage regimes in the ESPS of industrial enterprises are commented upon in [2-4]. This

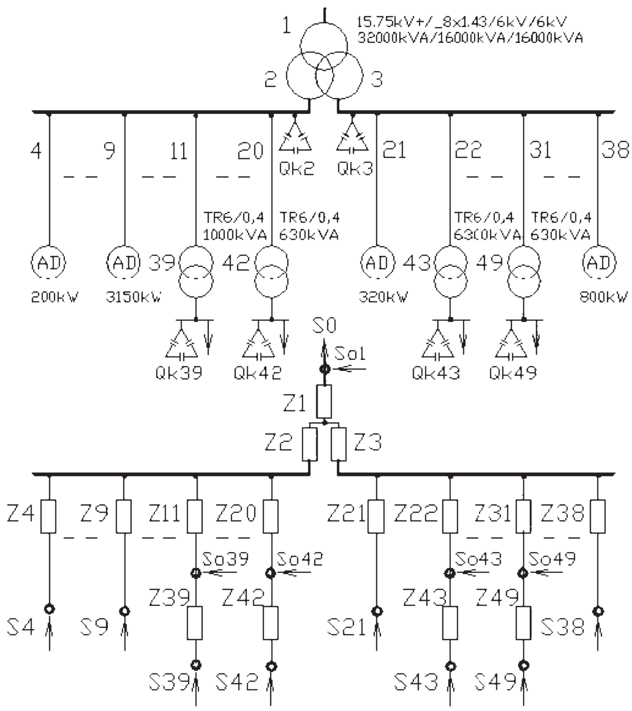

Fig. 1. Single-wire and substitute circuits of the ESPS

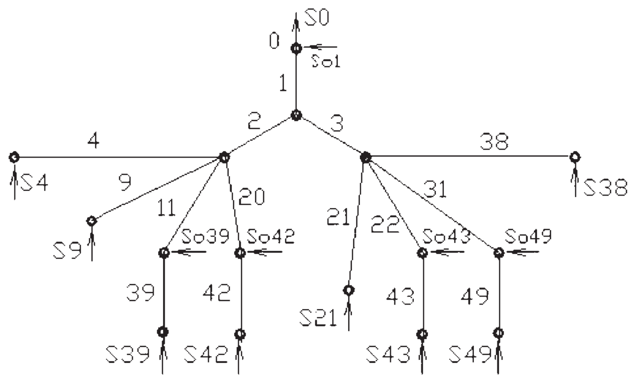

Fig. 2. Representation of the ESPS circuit as a graph diagram

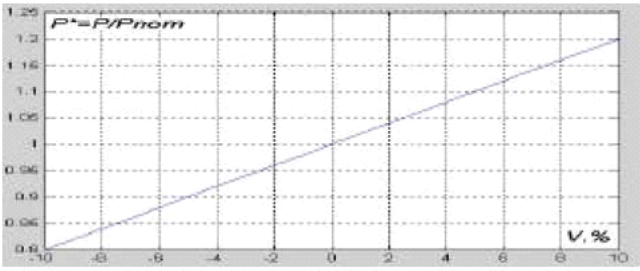

Fig.3a. Static characteristics of the active electric power of nodes 39-49 of the ESPS, P*=f(V)

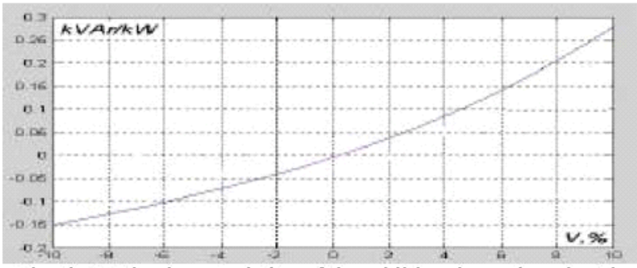

Fig.3b. Static characteristics of the additional reactive electric power of nodes 39-49 of the ESPS (dQ=f(V) [kVAr/kW], where Q=Qnom+dQ*Pnom)

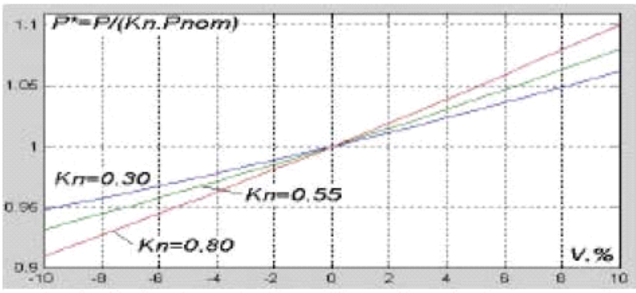

Fig.4a. Static characteristics of the active electric power of nodes 4-38 of the ESPS, P*=f(dU,Kn)

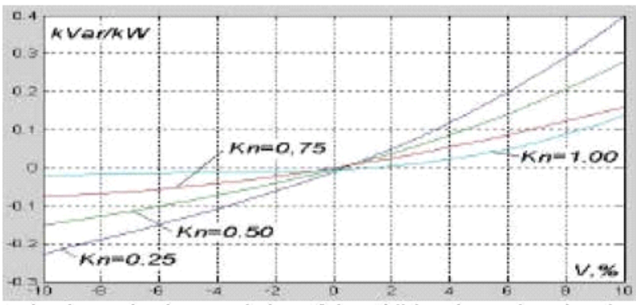

Fig.4b. Static characteristics of the additional reactive electric power of nodes 4-38 of the ESPS, (dQ=f(V,Kn) [kVAr/kW], where Q=Qnom+dQ*Pnom)

report describes the specifics of the algorithms for control of the voltage regimes of a particular ESPS. The following preliminary work is done in preparation for the implementation of the suggested algorithm: a single-wire and substitute circuits of the ESPS (Fig. 1), as well as a graph diagram of the connections (Fig. 2), are developed; the accuracy of the information obtained from the existing information system is verified; and the available information is entered in a database, where it is also sorted in order to be used by the computer serving as an advisor to the human operator.

An important part of the research is obtaining the static characteristics of the assigned electric loads. The latter research can be conducted without interrupting the normal operation of the electric devices – the change in voltage is done through the regulator in the MATS in the allowable ranges for the electricity consumers. This work is not completely finished yet, but examples of the static characteristics are given in Fig. 3-4.

B. Optimization Problem Objective and an Algorithm for Obtaining the Deviations of the Voltage

The main constraints in the optimization problem are the allowable deviations of the voltage at ESPS nodes at which there are assigned electric power loads. The objective function is to minimize the total electric power used by the self-service consumer department given hourly constraints on the power factor. This objective function is similar to the objective function described in [2] (minimize the loss of active electric power while transferring reactive electric power), but now the goal is to force the MATS electric consumers to use minimum total power. This allows a larger part of the energy produced by the thermo-electric power plant generators to be used in the national energy system. In addition, this guarantees minimal loss of power in the MATS.

The decision variables in the optimization problem are the supply voltage at the entrance of the MATS and the magnitude of the assigned electric loads in the ESPS.

In order to compute the voltages in the nodes of the ESPS using the matrix method [3], it is sufficient to have the supply voltage at the entrance of the MATS, the parameters of the substitute circuit, and the assigned electric loads in the ESPS. The solution of the system of algebraic equations is of the form $dU = Z.I$, where dU is a vector containing the total voltage-drops at the nodes of the ESPS, recorded relative to the entrance of the MATS; Z – a square matrix containing the coefficients of the contour impedances; I – a vector containing the contour electric currents in the ESPS [6]. For an open radial scheme, which is the scheme considered in this report, the measurement of the effective values of the electric current, the voltage, and the active electric power, is done at the exits of the MATS radial lines. In this case the recorded active electric power is higher than the actual electric power consumed by the devices because of the losses of active power in the lines. The latter losses, however, are not large because the lines are designed to be resistant to heat (the cross-section of the lines is big). This is particularly true in the case of high-voltage motors (6 kV). However, if a transformer substation 6/0,4 kV does not work at full capacity, the losses of active electric power in the transformer winding should be accounted for. When the loading of a transformer substation is determined mainly by a group of asynchronous motors with approximately equal loads, the deviations of the voltages at the terminals of the motors and the natural reactive electric power can be computed with reasonable accuracy using the following algorithm:

a) At the beginning it is assumed that the active power load $Pmeas$ and the reactive power load $Qmeas$ of the transformer substation are measured at the low voltage side of the transformer;

b) The deviation of the voltage at the low voltage side of the transformer is computed;

c) The load coefficient $Kn[j] = Pmeas[j]/Pmax[j]$ is determined. The additional reactive power dQ for that Kn is found (Fig. 4b). The current reactive power $Qcur = Qmax + dQ * Pmax$ at the low voltage side of the transformer is calculated;

d) The current compensating reactive power at the low voltage side of the transformer, $Qkcur = Qmeas - Qcur - Qo$, is calculated. Here Qo denotes the magnetizing reactive power of the transformer;

e) The losses of active power in the line and the transformer are calculated using the measured values of the active and the reactive loads ($Pmeas$ and $Qmeas$). The current value of the active power at the low voltage side of the transformer, $Pcur' = Pmeas - dP$, is computed;

f) The so-determined values for the loads at the low-voltage side of the transformer, $Pcur$, $Ocur$, and Qk, are then used as input to the optimization problem that solves for the optimal regime of voltages in the ESPS.

C. *Calculation of the Parameters of the Optimization Problem*

The relationship between the decision variables and the parameters in the ESPS can be described by the equations:

a) Total electric power at the entrance of the MATS: $S^2 = P^2 + Q^2$;

b) Active electric power at the entrance of the MATS: $P = Sum\{(Pcur[j] + dP[j]),\ j = 1..n\}$;

c) Reactive electric power at the entrance of the MATS: $Q = Sum\{(Qcur[j] + Qkcur[j] + dQ[j]),\ j = 1..n\}$;

d) Power factor at the entrance of the MATS: $\cos FI = \cos(\text{arctg}(Q/P))$;

e) Deviation of the voltage at node i: $V[i] = 100 * (U[i] - Unom[i])/Unom[i])$, where $U[i]$ is the current value of the voltage at node i, computed using the matrix method for the current value of the voltage $U[0]$ at the entrance of a MATS, the selected additional deviation of voltage Eqr_c, the current values of the assigned electric loads $(Pcur, Qcur)$, and the selected distribution of compensating reactive powers $Qkcur$ at the low voltage side of the transformers and the 6 kV side of the MATS;

f) Current value of the reactive power of line j: $Qcur[j] = Qmax[j] + Pmax[j] \cdot dQ(Kn, dU)$ – using the polynomials for dQ as a function of the deviation of the voltage V given a load coefficient Kn where $Pmax[j]$ is the maximum value of the active power of line j;

g) Allowable range for the deviation of the voltage at node i: $Vmin[i] \le V[i] \le Vmax[i]$;

h) Load coefficient of the assigned electric load of line j: $Kn[j] = Pmeas[j]/Pmax[j]$;

i) Allowable range for the current compensating reactive power of line j: $Qkmin[j] \le Qkcur[j] \le Qkmax[j]$; or $0 \le Qkcur[j] \le 0.62 \cdot Pcur[j]$;

j) Losses of active electric power in line j: $dP[j] = dPa[j] + dPr[j]$;

k) Losses of active electric power, caused by the active power in line j: $dPa[j] = R[j] * Pcur[j]^2/(100 + V[i])/100)^2$;

l) Losses of active electric power, caused by the reactive power in line j: $dPr[j] = R[j] * Qcur[j]^2/(100 + V[i])/100)^2$;

m) Losses of reactive power in line j: $dQ[j] = X[j] * (Pcur[j]2 + Qcur[j]^2)/(100 + V[i])/100)^2$.

The input data for the optimization problem are:

- The number of nodes in the ESPS: m;
- The number of lines (arcs) in the ESPS: n (for open graphs $n = m$); Deviation of the voltage at the entrance of the MATS (as a percentage of the nominal voltage): $V[0]$;
- Current additional deviation of the voltage of the Jansen regulator of the transformer in the MATS: Eqr_c;
- Available additional deviations of the voltage in the MATS: $Eqr[17]$=-11,44; -10,01;...; 0;...; +10,01 ;+11,44;
- The fixed additional deviations of the voltage in the lines, containing transformers that cannot be regulated when loaded: $E[j]$, $j = 1..n$;
- Maximum values of the assigned active and reactive electric loads in the ESPS: $Pmax(j)$, $Qmax(j)$, $j = 1..n$;
- Current values of the assigned electric loads at the nodes of the ESPS: $Pcur'(j)$, $j = 1..n$;
- Maximum and minimum values of the reactive electric load coming from the compensating devices in the ESPS: $Qkmax(j)$, $j = 1..n$; $Qkmin(j)$, $j = 1..n$;
- Values of the power factor for each hour of the day with upper limit $\cos FI \max[hour]$ and lower limit $\cos FI \min[hour]$ for $hour = 1 - 24$;
- Load coefficient: $Kn[j] = Pmeas[j]/Pmax[j]$;
- Static characteristics of the active and the additional reactive electric power for the assigned electric loads, described by polynomials for P and dQ as a function of the deviation of the voltage V given load coefficient $Kn[j]$: $P[j] = f(dU, Kn)$, $dQ[j] = f(V, Kn)$.

III. Optimization Problem Formulation

The optimization problem formulation is as follows:

Minimize	$S^2 = P^2+Q^2$	
Subject to	P=Sum{(Pcur[j]+dP[j]), j=1..n};	(C1)
	Q=Sum{(Qcur[j]+Qkcur[j]+dQ[j]), j=1..n};	(C2)
	Pcur[j]=Pcur'[j]*P[j];	(C3)
	$P[j]=f(V,Kn,P_{30},P_{55},P_{80})$;	(C4)
	cosFI<=cosFImax[hour]; cosFI>=cosFImin[hour];	(C5)
	V[i]=100*(U[i]-Unom[i])/Unom[i]);	(C6)
	Vmin[i]<=V[i]<=Vmax[i];	(C7)
	Qcur[j]=Qmax[j]+dQ[j] $dQ[j]=f(V,Kn,Q_{25},Q_{50},Q_{75})$;	(C8)
	$P_{[39-49]}=0,02*V+1,0$ $P_{30[4-38]}=0.00005*V^2+0.0057*V+1.0$ $P_{55[4-38]}=0.00006*V^2+0.0074*V+1.0$ $P_{80[4-38]}=0.00005*V^2+0.0095*V+1.0$	(C9)
	$dQ_{[39-49]}=0.0000353*V^3+0.00096*V^2+0.0277*V-0.0102$ $dQ_{25[4-38]}=0.0000353*V^3+0.00096*V^2+0.0277*V-0.0102$ $dQ_{50[4-38]}=0.00002*V^3+0.000686*V^2+0.0195*V-0.0043$ $dQ_{75[4-38]}=-0.0000033*V^3+0.00043*V^2+0.0121*V-0.00043$ $dQ_{100[4-38]}=0.000044*V^3+0.00065*V^2+0.0036*V-0.00583$	(C10)
	Qkmin[j]<=Qkcur[j]<=Qkmax[j]; or (0<=Qkcur[j] 0<=,62.Pcur[j]);	(C11)
	dP[j]=dPa[j]+dPr[j];	(C12)
	$dPa[j]=R[j]*Pcur[j]^2/(100+V[i])/100)^2$	(C13)
	$dPr[j]=R[j]*Qcur[j]^2/(100+V[i])/100)^2$;	(C14)
	$dQ[j]=X[j]*(Pcur[j]^2+Qcur[j]^2)/(100+V[i])/100)^2$	(C15)

The decision variables in the optimization problem are S, P, Q, $\cos FI$, U, V, $Pcur$, $Qcur$, dQ, $Qkcur$, dP, dPa, dPr. Constraints C1-C9 and C13-15 were discussed in Part C. From equations C9, using interpolation, one can determine the change in active electric power given the change in the deviation of voltage. From equations C10, using interpolation, one can determine the additional reactive electric power dQ for a particular value of the deviation of the voltage. Constraint C12 describes the available compensating reactive power at the nodes with assigned electric loads.

A. Applications

The suggested algorithm is implemented in Matlab in a reduced form since the research related to recording the static characteristics of the concrete ESPS is ongoing. At this stage, we do not have complete results about the behavior of the model in the real conditions of the ESPS in consideration.

IV. Additional Remarks

Concrete results about the behavior of the model will be presented after implementing the system. At the moment, we are working on algorithms and programs in C++ (for regime calculations) and in Delphi (for visualization and control). The calculations are designed to be done in real time through an embedded controller of the voltage regulator in the MATS. The regime of the voltages will be determined based on the variation in the assigned electric loads in the ESPS. The controller will transmit the information about the optimal regime to an IBM personal computer for visualization, and will retransmit the commands of the dispatcher for regime implementation.

V. Conclusion

The goal of this report was to describe the specifics of the model. There is a substantial amount of work to be completed for the model's full realization. Its implementation depends to a large extent on the management of the ESPS. If the necessary funding can be found and the system is implemented, a verification of the suggested algorithms (and possible corrections and changes) can be done.

Acknowledgement

The authors are very grateful to the executive manager of thermo-electric power plant "Bobov dol" for his cooperation and for allowing us to record data necessary for the research. We would also like to thank the on-duty and maintenance personnel of the plant, as well as our colleagues from the Electric and Automatic Devices Laboratories for their responsiveness and help in recording the static characteristics of the self-service consumer department of the thermoelectric power plant.

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