Control of the Voltage Regime of Electric Power Supply Systems in Industrial Enterprises

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

Abstract – **This report discusses the structure and organizational principles of a data acquisition and control system for maintaining an optimal regime of the voltages in an electric supply power system (ESPS) in an industrial enterprise. The voltages at the terminals of the consumers can be controlled through the regulator in the main adjustable transformer substation (MATS) as well as the compensating devices for reactive electric power in the ESPS. To this end, the assigned electric loads in the ESPS are measured periodically, and an optimization problem is solved in real time.**

Keywords – **Electric Power supply, Voltage Control**

I. Introduction

Maintaining an optimal regime of the voltages in the electric power supply systems of industrial enterprises is important for the improvement of the operating regime of electric devices that are sensitive to deviations of the voltage from its nominal value. Devices containing electromagnetic systems (electric motors, inductive ballasts of discharge lamps, start-stop devices with magnetic core) are sensitive to positive deviations of the voltage – the saturation of their magnetic cores is a reason for loss of active electric power, which leads to overheating and intensive wearing out of the insulation, increased noise, and unutilized additional loss of electricity. Significant deviations of the voltage below its nominal value are also undesirable. When there are lighting loads, such deviations reduce lighting yields (lm/W) because of inefficient operation of the lamps. The start moment of rotation of asynchronous motors decreases when the voltage decreases, which is dangerous for the work of important machines – if the basic machine fails and there is need for automatic start of a backup machine, the latter machine may not be able to start if the voltage is low. This necessitates defining the following allowable deviations of the voltage at consumer terminals: a) for lighting load with incandescent lamps +/-2,5%; b) for lighting loads with discharge lamps +/5%; c) for asynchronous motors +10%/-5%. Regulating devices and appropriate algorithms are used in order to ensure that these constraints are satisfied in an ESPS [1,2].

[1]Angel Pachamanov, Electric Power Supply and Equipment Department, Technical University – Sofia, pach@tu-sofia.bg

[2]Dimitar Bibev, Electric Power Supply and Equipment Department, Technical University – Sofia, dbib@tusofia.bg

[3]Dessislava Pachamanova, Babson College, Babson Park, MA 02457, USA, dpachamanova@babson.edu

II. Essence of the Problem

A. *Optimal Regime of the Voltages in an ESPS*

The dynamics of the active electric loads requires the voltage regime in ESPS in industrial enterprises to be determined in real time through periodic control of the loading of the transformer substations and of the motors that set in motion machines in power departments – compressor and thermal power departments, pump stations, etc. Since the loads at this level of the ESPS are symmetric, the converters of the electric parameters work in a single-phase mode [2]. Through telecommunication means [3], the information from the converters is sent to the dispatcher station of the industrial enterprise (Fig. 1), and the most appropriate deviations of the voltage of the transformer at the MATS as well as the optimal distribution of the compensating reactive power devices in the ESPS are determined.

If the active electric loads in the industrial enterprise are the approximately equal every hour of the day and night, the optimal voltage regime can be easily achieved. This is due to the fact that in the design of an ESPS, the selected deviations of the voltages in the department transformers correspond to the maximum values of the active electric loads. However, if the active electric loads vary significantly, the addition of deviations of the voltage in the MATS is not always sufficiently effective in managing the voltages at all terminals of the MATS. This is why, for example, for maintaining the optimal voltage of lighting loads, special devices such as transformers and electronic regulators are attached to the low voltage side of the department substation (Fig. 1). For

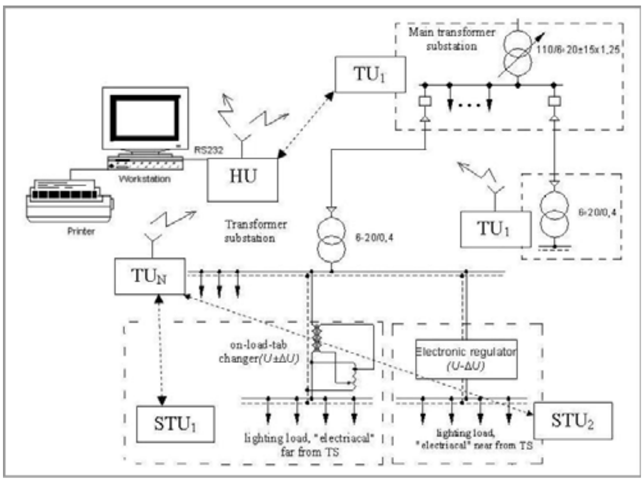

Fig. 1. Voltage control system in industrial enterprises

department substations supplying mainly asynchronous motors, the voltage regime can be influenced through redistribution of the reactive loads. Fig. 3a and Fig. 3b illustrate the dependence of the additional consumed active (respectively, reactive) power on the level of supplied voltage.

It is well known that the stable operating regimes of electric circuits with sinusoidal alternating current can be described by a system of linear algebraic equations with complex values – impedances of lines and devices, voltages at the nodes, assigned electric loads in the ESPS. These algebraic equations are also called state equations, and are constructed according to the substitute circuit of the ESPS. Given the voltage at the entrance of the industrial enterprise and current measurements of the magnitude of the assigned electric loads in the ESPS, the most appropriate method for solving for the stable voltage regime is the matrix method [1,6]. The optimal position of the voltage regulator in the MATS and the optimal distribution of the compensating devices for reactive electric power are determined by solving a concrete optimization problem for the given configuration in the ESPS [4]. The problem is solved in real time through a computing device (a controller or a computer) every one or one half hour. The obtained solution is implemented through control commands to devices – a voltage regulator in the MATS (the so-called Jansen regulator), compensating reactive power batteries in the ESPS, inducing coils of synchronous motors in power departments that produce reactive electric power.

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 selected according to the concrete requirements of the ESPS – minimize the loss of active electric power while transferring reactive electric power, minimize the total deviation of the voltages at the nodes of the ESPS without considering the loss of active electric power in transferring reactive electric power, and so on. In [4], the optimization problem is solved with objective function “Minimize the consumed total electric power used by the self-service consumer department given hourly constraints on the power factor”. This implies the greatest possible overloading capability of the MATS and minimal additional losses of electric energy in it. 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 addition to information about the current values of the entrance voltage and the assigned electric loads, the following data are necessary for solving the optimization problem:

- The current position of the Jansen regulator and the available degrees for regulating the voltage in the MATS;
- The maximum compensating reactive power in each department substation and the current state of the compensating devices for reactive power (batteries and synchronous motors);
- The static characteristics of the active and reactive electric power in the lines with assigned electric loads.

B. Static Characteristics of the Consumers

Lighting installations are most sensitive to increases in the supplied voltage, because the life of lighting sources can be greatly reduced, and the loss of active electric power in the ballast increases. In the case of discharge lamps, the reactive electric power also increases because of the increase of electric current through the inductive ballast.

Fig. 2 shows the change in active electric power of lighting installations with different lighting sources for voltage deviations between -10% and +10% [5]. Similar static characteristics of asynchronous motors are shown in Fig. 3 (for given load coefficient $Kn = P/Pnom$). It is recommended that the static characteristics for each consumer (substation) be recorded individually, because the type of the electric loads in each department can be different.

C. Input Information and Use

For effective management of the voltage regimes, it is important to determine the type and the quality of the information reaching the dispatcher station. The construction of a control system with different types of measuring devices (for voltage, electric current, active and reactive electric power), in addition to being expensive, is also unnecessary. The main question is the accuracy of the received information. The measurements from different devices frequently provide contradicting information when verified by theoretical means. Our experience shows that it is more appropriate for all necessary parameters (the effective value of the voltage, the effective value of the electric current, and the active electric power) to be obtained from a single measuring device. By recording the current values of the electric current and the voltage (through scanning using microprocessor devices), it is possible to calculate all other parameters mentioned above [2].

As was already discussed, in order to compute the voltages at the nodes of the ESPS using the matrix method, it is sufficient to have information about the voltage at the entrance of the plant, the parameters of the substitute circuit, and the assigned electric loads in the ESPS. The solution to the system of equations gives the voltage-drops up to the terminals of the consumers: $dU = Z.I$, where dU is a vector containing the total voltage-drops at the nodes of the ESPS relative to the voltage at the entrance of the plant (assumed to be zero); Z – a square matrix containing the coefficients of the con-

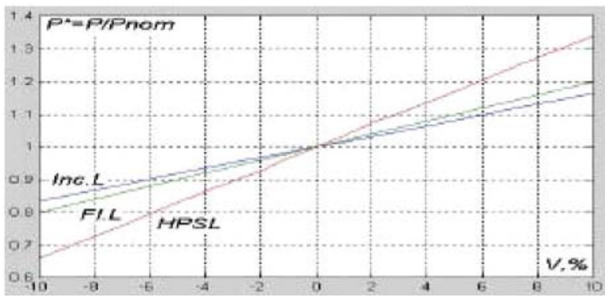

Fig. 2. Static characteristics of the active electric power of different types of lamps, $P* = f(V)$

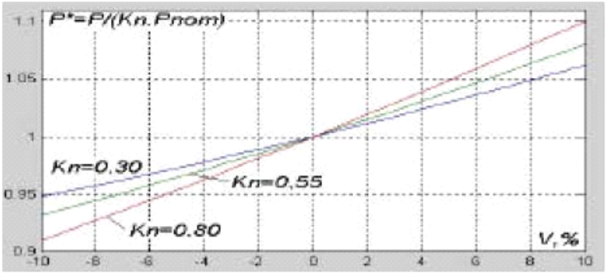

Fig.3 a. Static characteristics of the active electric power P*=f(V,Kn) of asynchronous motors (P=Kn .Pnom.P*)

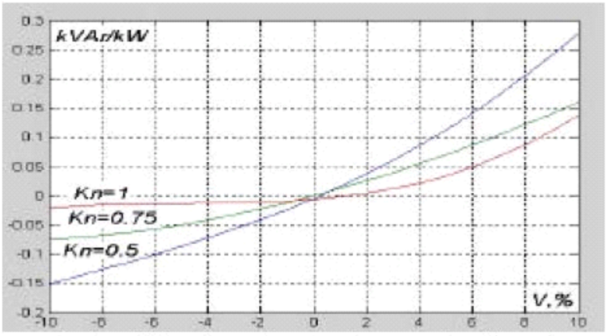

Fig.3b. Additional reactive electric power dQ=f(V,Kn), [kVAr/kW] for asynchronous motors (Q=Qnom+ dQ*Pnom)

tour impedances; I – a vector containing the contour electric currents in the ESPS [6].

For open radial schemes, which is the case with most electric supply power systems in industrial enterprises, the measurement of the effective values of the electric current, the voltage, and the active electric power is usually done at the exits of the MATS radial lines. 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. High-voltage lines are designed to be heat resistant and their cross-section is big, so the loss of active electric power in them is small and can be ignored. However, if the deviations of the voltage have to be calculated for the low-voltage side of transformer substations 6-20/0.4 kV, the loss of active power is more significant and should be accounted for. In the latter case, the computation for the voltage at the terminals of the consumers can be done with reasonable accuracy using the algorithm suggested in [4].

D. Description of the Optimization Problem

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: $Eqr[25] = -15.0;\ -13.75\ ; ..; 0\ ; ..; +13.75\ ; +15.0$;
- 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 electric loads in the ESPS: $Pmax(j), Qmax(j),\ j = 1..n$;
- Currently measured values of the assigned electric loads in the ESPS: $Pmeas[j],\ Qmeas[j];\ j = 1..n$;
- Load coefficients: $Kn = Pmeas[j]/Pmax[j],\ j = 1..n$;
- Maximum and minimum values of the reactive electric load coming from the compensating devices in the ESPS: $Qkmax(j),\ j = 1..n;\ Qkmin(j),\ j = 1..n$;
- 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 $Kn[j]$: $P[j] = f(dU, Kn), dQ[j] = f(V, Kn)$.

The objective function and the constraints of the optimization problem are described as follows:

a) Total losses of active electric power in the lines and devices of the ESPS: $dP = Sum\{dP[j],\ j = 1..n\} = \min$;

b) The total power at the entrance of the MATS has to be smaller than the nominal power of the transformer: $S^2 = P^2 + Q^2 \leq Snom\_tr$;

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

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

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

f) Lower limits on the power factor for some hours of the day: $\cos FI = \cos FI \min[hour]$;

g) Upper limits on the power factor for the remaining hours of the day: $\cos FI \leq \cos FI \max[hour]$;

h) Allowable range for the current compensating reactive electric power in line j: $Qkmin[j] \leq Qkcur[j] \leq Qkmax[j]$; or $0 \leq Qkcur[j] \leq 0.62 \cdot Pcur[j],\ j = 1..n$;

i) Current value of the active electric power of line j: $Pcur[j] = Pmax[j] \cdot P(j)$;

j) Change in the active electric power for given load coefficient and deviation of the voltage: $P = P(Kn, V)$ – calculated from polynomials;

k) Current value of the reactive electric power of line j: $Qcur[j] = Qmax[j] + Pmax[j] \cdot dQ$;

l) Additional reactive electric power for given load coefficient and deviation of the voltage: $dQ = dQ(Kn, V)$ – from polynomials;

m) Deviation of the voltage at node i: $4V[i] = 100*(U[i] - Unom[i])/Unom[i])$, 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 the 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;

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

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

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

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

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

E. Applications of the Suggested Method

The implementation of the described method has been done in Matlab (with a concrete objective function) for the electric supply power system of the self-service consumer department of a thermo-electric power plant – the completed preparatory work (collecting current information, study and verification of the substitute circuits in the ESPS, representation of the substitute circuits as a graph) is described in [4]. The system is planned to have a role as an advisor to a human operator (as opposed to an independent controller) because of the big responsibility associated with the safety of running the processes the thermo-electric power plant. A printout with the optimal regime will be presented to the dispatcher every hour. The printout will contain: a) recommended position of the Jansen regulator; b) recommended distribution of the compensating reactive electric loads in the MATS; c) sequence of the commands the dispatcher needs to transmit in order to achieve the regime recommended in a) and b). The visualization of the ESPS is done through a PC monitor: the current levels of the voltage at the nodes of the ESPS are continuously updated on the screen.

III. Additional Remarks

Significant preparatory work is needed for the implementation of the suggested algorithm. The first stage consists of the creation of the substitution circuit scheme in the ESPS, its representation as a planar graph, and the development of tools for calculations necessary for determining the optimal voltage regime. A very important part of the research is recording the static characteristics of the assigned electric loads in the ESPS and describing them via polynomials. The next step is designing and developing a data acquisition and control system. The main part of this system is installing measuring devices (for the effective values of the electric current, the voltage and the active electric power in the lines) and execution devices (for control of the compensating reactive electric loads). This part is easy to implement through available and convenient for exploitation microprocessor systems and telecommunication means [2,3].

IV. Conclusion

The most significant part of systems for optimization of the voltage regime, namely obtaining with sufficient accuracy the static characteristics of the assigned electric loads, can be done relatively easily if the implementation of the system begins with its data acquisition part. While installing the execution devices and developing the algorithms for control, the already implemented database is continuously updated with all random changes in the voltage, in the active and the reactive electric power, and in the connected compensating reactive electric devices in the ESPS. After statistical analysis of the recorded data, confidence intervals for a desired level of significance can be created for the static characteristics of change in the active and reactive electric power of the assigned electric loads given a change in the deviation of the voltage. At the final stage of implementation, the system is re-programmed and turned from data acquisition to data acquisition and control system.

Acknowledgement

The authors would like to thank Prof. S. Siderov, chairman of the Electric Power Supply and Equipment department of the Technical University in Sofia, for his responsiveness and his valuable advice in the development of the program for analysis of the voltage regimes that was used in the implementation of the optimization algorithm.

References

[1] Siderov S., A. Pachamanov, D. Bibev. An algorithm and a computer program for analysis of the voltage regime in industrial enterprises. Smolian'2001

[2] Bibev D., A.Pachamanov. Control and monitoring of voltage for lighting systems in industrial enterprises. ELMA02, Sofia, September 13-14, 2002

[3] Matanov N.,R.Pachamanov, D.Bibev, A.Pachamanov. Using GSM-modules for control of street lighting and industrial electric power supply systems. Energetic and information systems and technologies. 2003, October 16-18, TU-Sofia

[4] Bibev D., D.Pachamanova, A.Pachamanov. An optimization-model for determining the optimal voltage regime in industrial electric power supply systems. Energetic and information systems and technologies. 2003, October 16-18, TU-Sofia

[5] Kungs, Ia. A. Automatization of the control of electrical lighting, Energoatomizdat. Moscow, 1989

[6] Melnikov, N. A. Matrix method for analysis of electric circuits, Energia, Moscow, 1972