Increasing the Energetic Efficiency in Producing of Electric and Thermal Power in Thermal Power Plants by Using of Variable Speed

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Abstract: - In this work is presenting a theoretical analysis and an experimental application of the energetic efficiency increase by using of variable-speed AC electric drive systems in a thermal power plant that produces electric and thermal power. Are presented few possible drive systems, both at low voltage and medium voltage, and is analysed the influence upon the curent's and voltage's wave shape due to the distorsions introduced by the adjustable drives.

The presented application refers to the distribution system of the produced thermal power, composed by the pumping station of the primary heat carrier, the district heating stations and the automation system. The experimental results from the first operational year are used to optimize the system.

Key-Words: Asynchronous motor, Static frequency converter, Harmonic distorsion generated by adjustable speed drives, District heating system, Pumping station, Testing, Energetic efficiency.

1 Introduction

The variable speed drives (VSD) which are used for pumps and fans applications (defined by the square shape of the torque vs. speed characteristic) are covering approximately 40% from the total amount of the electrical power required for all applications fig. 1 [1, 2].

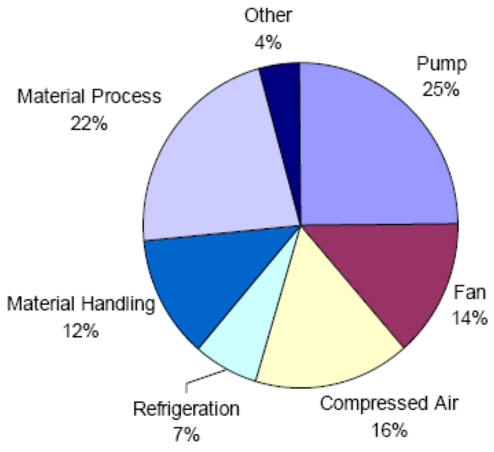

Fig.1. Spreading of the installed power through VSD, for different applications

In the same time, the technical potential regarding the cost reduction, for different applications, brings for the first page also the pumps and fan systems, fig. 2 [1,2,3,4,5].

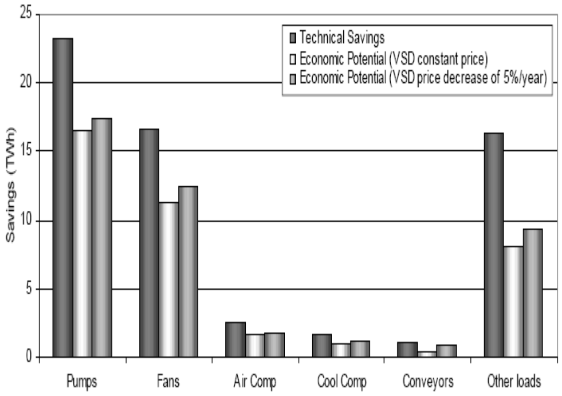

Fig.2. Technical potential for costs reduction for different applications

These issues led the specialists in this field to focus their attention for an improvement of this category of hardware: on one hand, pump and fan manufacturers have made technological progress that has led to a considerable increase of this equipment reliability and efficiency, and on the other hand the power and automation equipment manufacturers have substantially contributed to the electric power consumption optimization [1,2,6].

This latter issue highlighted two action categories:

- Utilization of power electronics equipment to supply electric drives, that allowed effective dosing of energy to the electrical machine, with the possibility of controlling one of the mechanical parameter (speed or shift torque);
- Automation of pumping and ventilation processes, which led to the subjective factor elimination, with its negative impact.

The positive impact of the power electronics equipment on electric drives performances results from European Community market shares. Fig. 3 presents, for different power ranges, the percentage of the variable speed drives from all electric drives with asynchronous machines [1,2,4].

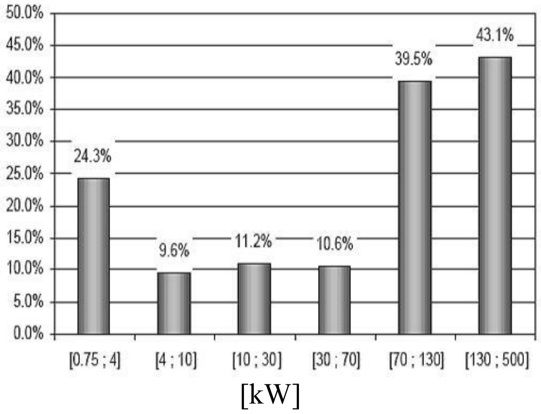

Fig.3. Weight of variable speed drives related to the power range

One can see that the high-power adjustable electric drives have the largest distribution due to the electronic equipment's cost reduction per kW by increasing the power. The paper presents the implications regarding the energetic consumption reduction as result of using systems with VSD for asynchronous motors in termo power plants.

2 Speed adjustment diagrams at the high-power asynchronous motors

In the Romanian thermal power plants the high-power electric drives of 160 kW are supplied at a voltage of 6 kV. The adjustable drives with powers up to 2.5 MW manufactured worldwide have supply voltages of 0.4 or 0.69 kV. For higher powers, there are solutions of medium voltage converters (3.3 kV, 4.2 kV or 6 kV).

For the drives supplied at 6 kV that are wished to be adjustable, there were developed two diagram types, one with low voltage converter (fig.4) and one with converter at 6 kV (fig.5). [4].

By means of the voltage-drop transformer (LT) the voltage is adapted according to the needs of the static frequency converter (SFC). At the converter's output, due to the deformation of the wave shape, is necessary a sinusoidal filter (SF) followed by the voltage-raise transformer (UT).

The sources selection, 6 kV from SFC or from the mains, is made by means of the source selection panel (SSP). The need of the 6 kV source from the mains is imposed in case of an SFC defect/failure. The solution from fig. 5 is more simple, but the SFC's cost is very high [4].

The chosing mode of one of the two solutions (fig.4 or fig.5) depends on the drives power, on the equipments' location possibility, on the existence of a sufficiently strong low voltage source, etc.

Adjustment of the charging of the thermal power plant generators (currently 3 MW/min), depends on the speed reaction of the automation system's components and on the boiler's inertia. Is imposed that the adjustment elements (coal flow, hot air flow, water flow at the boiler's intake and the waste gas flow) to be controlled safely and in real time.

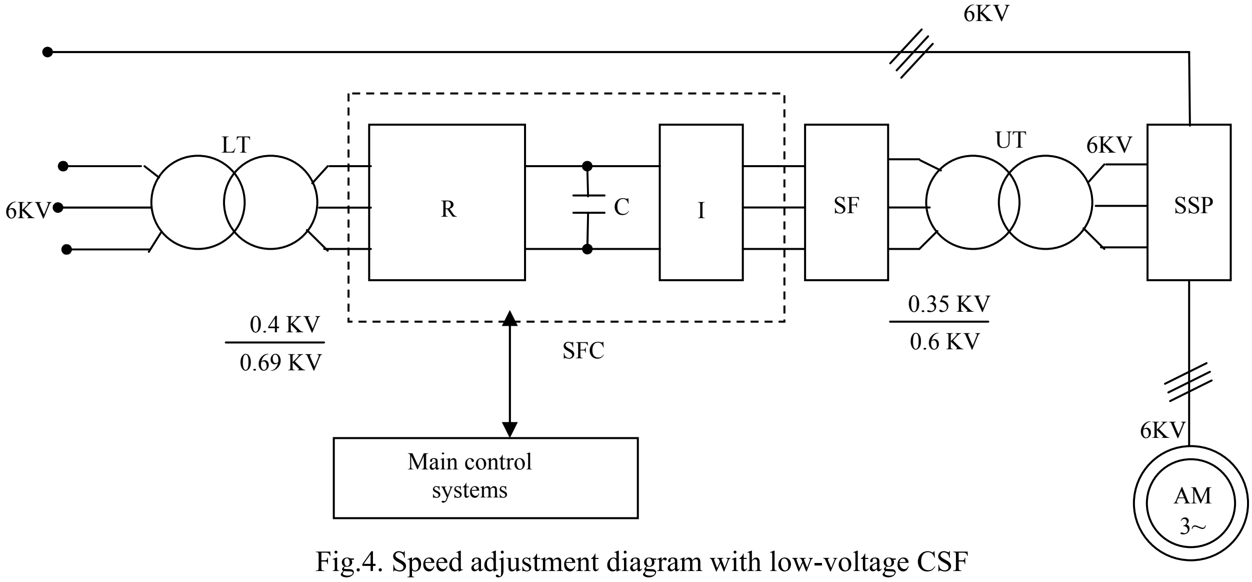

Fig.4. Speed adjustment diagram with low-voltage CSF

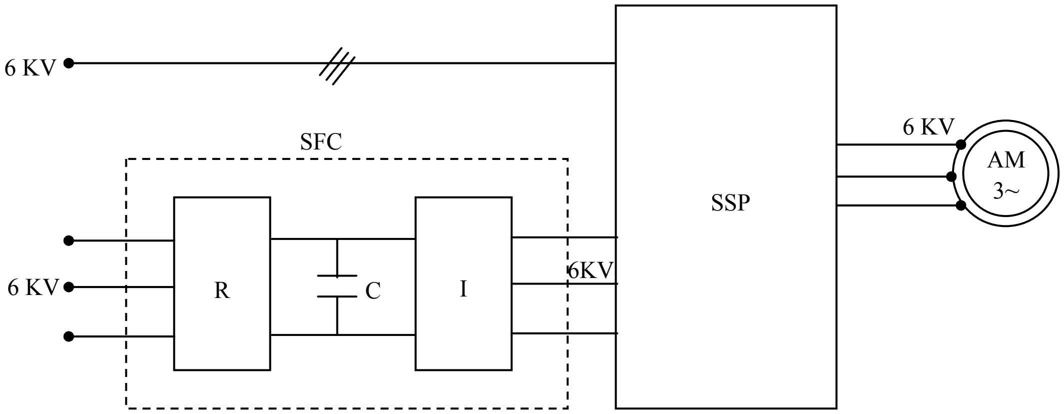

Fig.5. Speed adjustment diagram with CSF supplied directly from 6 kV

The speed adjustment solution with static frequency converters for the ventilators', pumps' and coal belt conveyors' motors is imposed to be the most viable one.

The drive motors of the coal belt conveyors (CBC) are supplied from low-voltage SFC. For the motors from the air ventilators (AV), waste gas ventilators (WGV) and the boiler's water supply pump (WSP) is chosen a speed adjustment diagram (SAD) suitable to the group's concrete situation.

3 Harmonic distorsions due to the high-power adjusting drives

The industrial AC Adjustable Drives (ASD) became a significant non-linear load component for the power distribution system, responsable for a serious harmonic polution of the supply system.

In the last years, major efforts have been focused on harmonic assessment and reduction techniques, as an important aspect of power quality management [7,8].

The purpose of an inverter is to chance a DC input voltage to an AC voltage of a desired magnitude and frequency. Practically, the real-time switching control can be deduced using pulse-width-modulation methods. The changeable inverter gain provides an efficient control drive. A variable inverter output voltage can be obtained by varying the of the inverter, which is achieved using pulse-width-modulation (PWM). This technique causes a discontinuity in the inverter output voltage and harmonics are produced. Therefore, many techniques are developed and tried to reduce the harmonic contents of inverter output voltage and getting acceptable inverter operation base do low distorted sinusoidal output voltage.

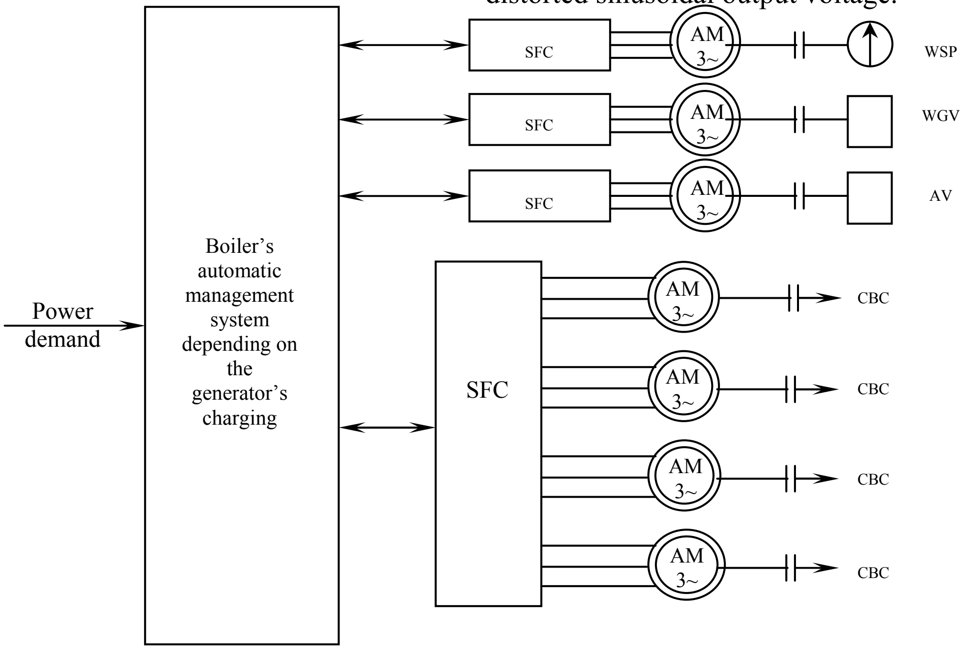

Fig.6. Boiler's automatic management using drives with asinchronous machines and frequency static converters

The most common types of switching techniques are the single-pulse-width-modulation, uniform pulse-width-modulation. All are trying to improve the performance of the inverter operation [9].

Instead of keeping de pulse width fixed, the width of each pulse can be changed using the sinuoidal-pulse-width-modulation technique. The width of each pulse depends on the amplitude of the sinusoidal reference signal. The Fourier series of the inverter's output voltage is given by the following equation:

$$v_0(t)=\sum_{n=1}^{\infty}\left[\sum_{m=1}^{2p}\left[\begin{array}{c}\dfrac{4V_d}{n\pi}\sin\dfrac{n\delta_m}{4}\\ \mathrm{x}\left\{\begin{array}{l}\sin n\left(\alpha_m+\dfrac{3\delta_m}{4}\right)\\ -\sin n\left(\pi+\alpha_m+\dfrac{\delta_m}{4}\right)\end{array}\right\}\end{array}\right]\right]\sin n\omega t \quad (1)$$

where:

P - the number of pulse per half-cycle;
m - the pulse-number;
δ_m - the variable pulse width;
$\upsilon_0(t)$ - the inverter output voltage;
n - the harmonic order;
V_d - the DC supply voltage;
α_m - the initial phase;
ω - pulsation

The harmonic distorsion factor is reduced compared to the single PWM technique and uniform PWM technique [9,10,11].

A non-linear current-distorting load, connected to an electric supply network, at a *Point of Common Coupling* (PCC), produces a voltage distortion, due to the voltage drop across the source (line) shortcircuit impedance, $Z_s=R_s+j\omega L_s$, fig. 7 [7,8]:

$$\underline{V}_h=\underline{Z}_s.\underline{I}_h=(R_s+j\omega.L_s).\underline{I}_h \quad (2)$$

In such a manner, the linear loads connected in PCC, are "overcharged" with a distortion (harmonic) active power, resulted from the harmonic currents injected into the line by the distorting load [7,8].

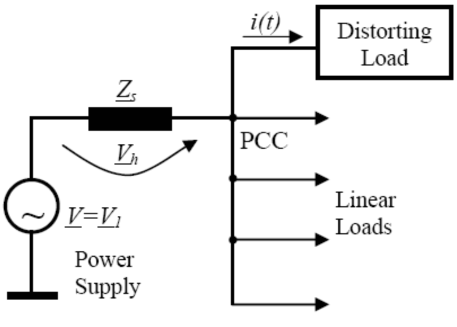

Fig.7. The mechanism of line voltage distortion

4 The pumping and automation for district heating system

Until the appearance of the variable-speed alternating current electric drives (VSD), the main adjusting element in the pumping systems was the valve operated manually, hidraulically or electric. The energy losses on the valve are extremely high and, moreover, the adjusting is not continous. Is estimated that, depending on the flow's dynamism degree, the losses could oscillate between (10÷40)% from the total consumed energy. Among the important electric power consumers are also the pumping and ventilation systems [3,4].

The automation of these systems and increase of their energetic efficiency can be made using static frecquency converters to adjust the speed of the pump's or ventilator's drive motor, adjusting in this way the flow of the transported fluid by keeping constant some parameters (pressure, level, etc.). The automation solution includes the utilisation of some data communications and transmission systems and PLCs, and is not unique. Therefore, the tests performed at commissioning and the further experimentations can lead to obtaining the necessary data to improve and optimize the initial system. [5].

Electrical systems are both convenient and safe if properly design, installed, maintained and used carefully, otherwise they can be a workplace of hazard, electric shock, electrocution, etc.

Reducing the risks for human life and electrical installations is required for insuring the general electrical safety [12].

Heating the houses from the urban environment in the cold season (october-april) is a necessity and this can be achieved using own systems (individual heating stations by solid, liquid or gas fuel) or centralized systems.

The centralized heating systems are the most efficient if they fulfill certain requirements. They must be flexible, dynamic, completely automated and to have a maximum possible energetic efficiency.

The wiring systems (cables and accesories) should be installed in positions that prevent mechanical damage, chemical or heat effects, otherwise additional measures shall be taken [12].

The district heating stations must ensure the need regardless its variation, by closing or opening the diaphragm at the heat exchanger's entrance. This modification determines the variation of the pressure drop Δp_k on the heating station detected in the primary supply circuit with heat carrier. For a real-time monitoring of these variations is necessary that the pumping system of the primary heat carrier to be provided with the possibility to modify the flow in order to keep constant the pressure difference between the circuit's tour (P_T) and retour (P_R):

$$\Delta p = P_T - P_R . \quad (3)$$

In fig.8 is presenting the block diagram of the primary heating circuit of a city.

In fig.8 were made the following notations: PHCPS – primary heat carrier pumping station; HE – heat exchanger; HS_1 … HS_n - heating stations; AS - automatic systems; PTT – pressure transducer on tour; PTR – pressure transducer on retour; TTT – temperature transducer on tour; TTR – temperature transducer on retour.

Each consumer has the possibility to establish his desired heating regime. The thermal energy consumption varies depending on season and outer temperature during a day, and also depending on other parameters.

The pumping station has more pumps in parallel, out of which one with variable speed. At a given moment, is started one or two of the fix-speed pumps and the variable-speed pump. The total pressure drop in the network is:

$$\Delta p = \Delta p_1 + \Delta p_2 + ...\Delta p_k + \Delta p_n . \quad (4)$$

The total pressure drop is the value aimed to be kept constant by increasing or decreasing the pressure on tour P_T.

At decreasing of Δp, the variable-speed pump will accelerate, and at increasing of Δp the pump will brake down to a speed that achieves the prescribed value for Δp.

In the warm season, only the variable-speed pump is functioning. The characteristic of this pump for the presented systems are: Q = 1000 m^3/h, h = 120 m, P_N = 367 kW. To achive these requirements, it was conceived the power and automation system presented in fig. 9.

In fig. 9 were made the following notations: ES – electric station; CC – control chamber; VAMP 3100 – medium voltage protection relay (6kV); VDET – voltage-drop electric transformer as dry construction (630 kVA, 6000V/400V); SFC – static frequency converter (450kVA, 400V, 800A); M – electric motor (400 kW, 400V, 750A, n_N = 1493 rot/min, $\cos\varphi_N$ = 0,91); P – pump; LCB_1, LCB_2 – local control boxes; EV_1, EV_2 – electrovalve (ϕ 300 mm); α_1, α_2 –electrovalve's opening angle; P_T, P_R –tour's and retour's pressure; T_T, T_R – primary heat carrier's temperature on tour and retour; T_1, T_2, T_3 – temperatures in the electric motor's winding; T_4, T_5 - temperatures in the electric motor's bearings; T_6 – temperature in the pump's bearings; T_7 – temperature of the transformer's windings; T_8 – temperature in the frequency converter; U_1 – supply voltage in the transformer's primary; U_2 – voltage in the transformer's secondary; I_1 – current absorbed by transformer; I_2 – curent absorbed by motor; P_1 – active power absorbed by transformer; Q_1 - reactive power absorbed by transformer; P_2 – active power absorbed by motor; n - motor's speed; PC – process computer.

The VSD, for many applications had problems of frequent tripping of the drives because occurs over-voltage in AC voltage supply. Each tripping caused lost production and severe production disruption. A possible cause of over-voltage is the closing of capacitor banks (used for improving the power factor) from substations. Setting the overvoltage protection must be carefully made. The solution lies in reducing the over-voltage value through installing surge protection device [13].

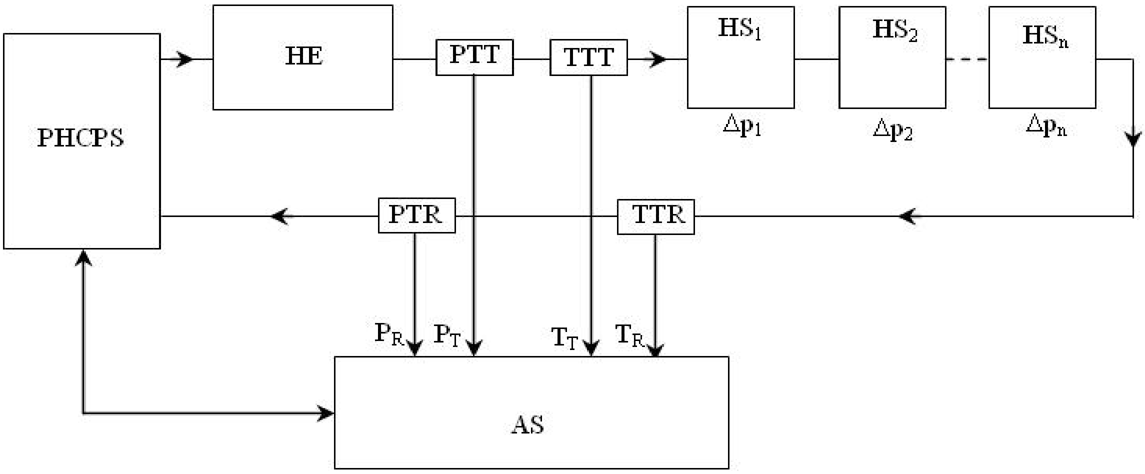

Fig.8. The principle diagram of a modern urban district heating system

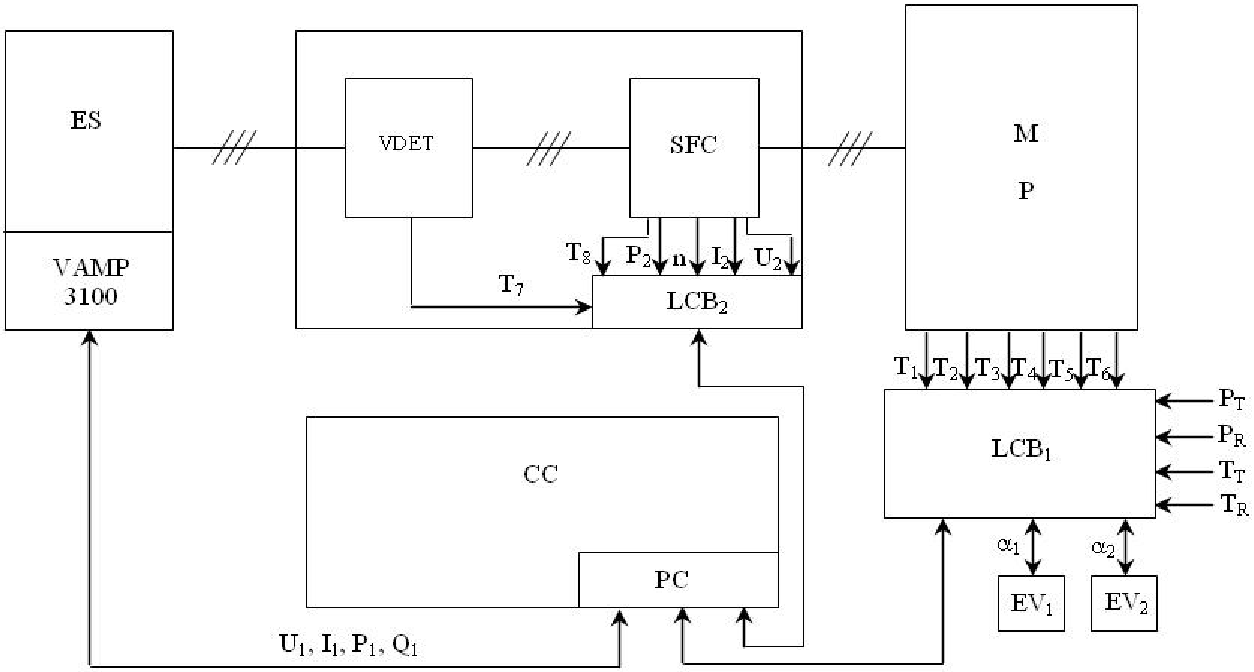

Fig.9. The principle diagram of the power and automation system

A lot of factors may influence bearing life in induction motor supply from inverter: loading, speed, mechanical shock, lubrification, vibration, operating conditions. An accelerated bearing current damage is possible when an induction motor is operated on non-sinusoidal inverters. A solution to increase the bearing's life is to use soft-switch inverters that reduce the drive carrier frequency and dv/dt decrease [14].

An overvoltage in long cable drives occurs when the voltage pulse from the inverter is reflected from motors terminals due to the mismatch between the difference between the cable impedance and motor impedance. To mitigate the overvoltage problems, in VSD can be used several filtering techniques. The overvoltage's characteristics are dependent to the voltage's harmonic spectra [15].

An electrical VSD have a power modulator, an electrical motor, a drive control unit, a sensing unit and an operator input.

Operator's panel is used to increase or decrease the speed of electrical drive. The drive control unit modulates the power from the source to the electrical motor. Depends on power modulator design, it is possible to control the speed, torque and power from electrical source to electrical motor. From a fixed DC voltage (using a rectifier), the inverters ensures a variable-frequency AC voltage to supply electrical motors. A variable voltage and variable frequency AC voltage can be obtained through PWM technique to control the inverter.

For inverter are used power electronic components such as diodes, transistors and so on, and are used in the non-linear switching mode.

A VSD are ussualy supplied as stand-alone units in the following configurations: IP00 rating (designed for chassis mounting), IP20/30 rating (designed for mounting in a clean environment that should be free of dust, moisture and contaminants); IP 54 (designed for mounting outside in sheltered environment) [16, 17].

An AC converter requires a three-phase feeder cable (copper or aluminium) and a PE conductor (copper) and usualy a neutral conductor is unnecessary.

In the cable between inverter and electrical motors results a higher level of harmonics (the frequency spectrum is between 100kHz-1MHz) than the power supply cable. This cable should be screened and the control and communications cables should not be located close to this cable.

The AC converter for start/stop control with contactor on the supply side or motor side of the AC converter should be avoided because occur operating problems.

The manual controls of VSD may be replaced with automated control system using PLC's and the wired control connections have been extended. Control systems have grown in complexity and information from a field sensors has expanded the number of conductors [17, 18, 19].

It was chosen the solution with voltage-drop transformer, frequency converter at 400 V and feeder cable of the low voltage motor because is more advantageous economically than the converter direct to 6 kV (it is cheaper with 30 to 50 % for low voltage applications). In the electric station was not enough space and it was adopted the solution to use a container placed close to the 6 kV station and the control room [4].

The local boxes LCB_1 and LCB_2 are placed in such way to centralize as more signals and to transmit them further to the process computer for processing in order to monitor the system's operation and protection. Also, by their means are controlled also the execution elements (valves, frequency converter, etc.). The relay from the medium voltage cell (VAMP 3100) protects the operation at the respective voltage level and transmits data regarding the electric parameters.

The commutation is serial, of MODBUS type.

The local boxes are provided with anti-condensation heating resistences, and the container with the transformer and frequency converter are provided with ventilation system which ensures the evacuation of the heat abstracted by losses.

The static frequency converter (of ACS 800 type) adapts its output frequency depending on the reference imposed by Δp_i and the pressure difference measured in Δp system by means of an internal regulator of auto-adaptive control PID type.

The process computer has as interface with the user a terminal of „touch screen" type that offers the operator a synoptic diagram of the automated system, the momentary data of the required values, the history of the variation in time of these values and the alarms and damages produced. The software application was achieved with the WIZCON 3.1. programming environment.

5 Experimental results

For commissioning, have been passed more steps. At the beginning were made the opening and closing tests of the electrovalves (valves) controlled from the local box or control room. The 6 kV cell was put under voltage, was checked the communication with the protection relay (VAMP), were simulated defects (short-circuit, overload) in order to track its feedback speed. By shutting-off the 6 kV switch, it was supplied the transformer, then the static frequency converter, monitoring on the application's screen the electric or thermal values. The motor was started as idle (without being coupled with the pump) in order to see the rotation sense, vibrations, the current absorbed at different reference values. After the mechanical coupling with the pump, was started its rotation with the valves closed at the beginning, then with the valves open, were measured the vibrations and the noise level and were imposed different values of the reference Δp_i monitoring the reaction mode of the entire system.

The load tests were made in case when in parallel with the variable-speed pump has operated also a fix-speed pump, and then the fix-speed pump was discoupled, remaining only the variable-speed pump. It was noticed that the pressure Δp adjusted within 7÷9 barr can be kept by the pump (functioning alone in the system) even at bigger flows than the nominal flow (was reached to Q_{max} = 1150 m^3/h and Δp = 8 barr). Were measured the currents and voltages at the output from the static frequency converter for diverse dynamic operation regimes, presented in fig. 10,11,12 and 13.

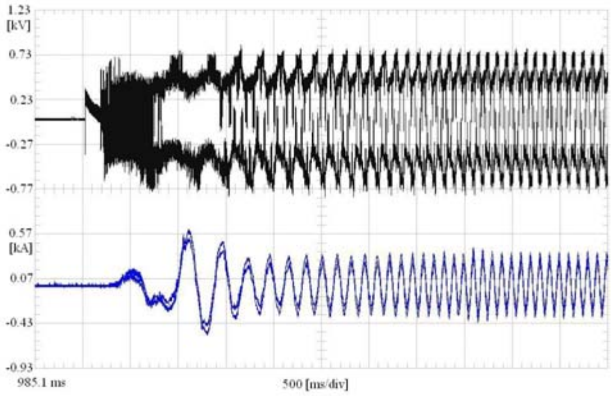

Fig.10. Voltage and current at the SFC output at start-up for a reference of 20%

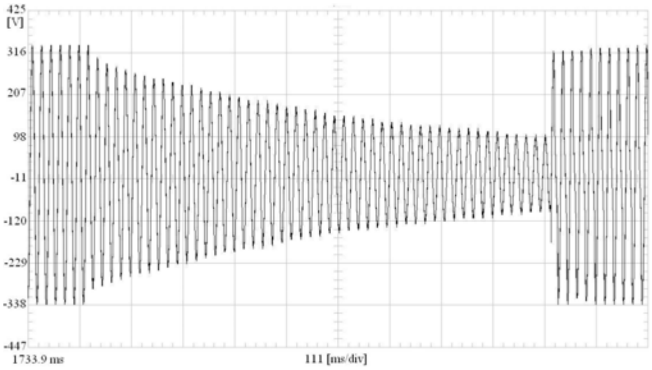

Fig.11. Voltage at the SFC output in case of shutting-down and restarting the pump

In fig. 10 are presented the current's and voltage's variation forms when receiving a reduced reference (20%) for the SFC regulator. After few oscillation periods is going into normal operation.

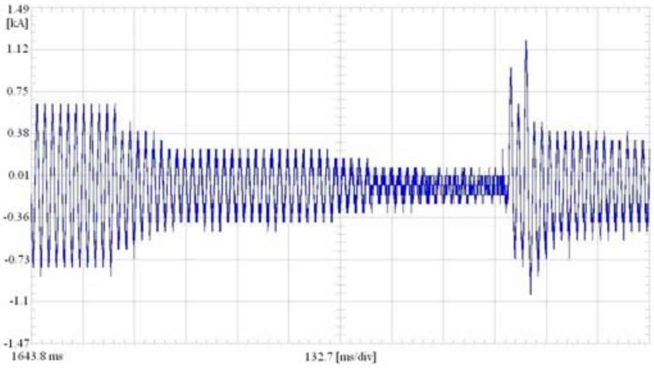

Fig.12. Current at the SFC output in case of shutting-down and restarting the pump

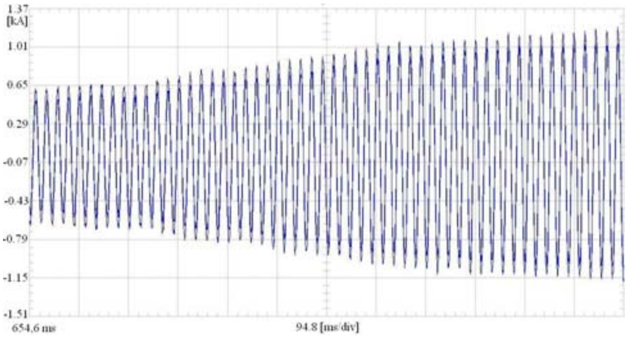

Fig.13. Current at the SFC output when in the system remains only the variable-speed pump (the fix-speed pump is stopped)

At shutting-down then restarting the pump, the voltage and current (fig. 11 and 12) have a smooth decrease during few periods, followed by a sudden increase and an oscillation duration after restart. The current has few negative and positive peaks of important values due to the check valve from the hydraulic circuit which was closed and now must be forced to re-open [6].

The moment of remaining in the system only the variable-speed pump (the fix-speed pump which operated in parallel was stopped) is caught in fig. 6, from here being possible to determine if the SFC regulator is well adjusted. One can observe that the pump remained alone is in overload regime.

Avoiding of long-term overloads is made by limitting the current at the SFC output in such way to be not produced overheatings of the pump's drive motor.

During the 72 hours test, which ended the experimentations at commissioning, the temperatures of the motor's windings were between 80÷85^{0}C, and in the bearings were 25÷30^{0}C at the bearing near-by the ventilator, and 40÷45^{0}C at the oposite bearing (the one towards the coupling). The oil temperature from the pump's bearing, of the transformer's windings and the converter's radiators (T_8 = 79÷80^{0}C) were framed in the normal limits. The problems appeared during experimentations were used for adjustments of the de communication and control software [6].

6 Increasing the energetic efficiency of the district heating system

Before modernization, keeping the pressure between certain limits in the system was made by closing or opening the diaphragms at the entrance in the heat stations. Automation of the heat stations didn't allow anymore these operations and it was imposed also the modernization of the pumping system of the primary heat carrier by means of a variable-speed pump.

The commissioning of the new system took place in April 2007. Based on the measurments of the energetic consumptions on 2006 and 2007, resulted that up to the end of 2007 (after 8 months of operation) the electric power savings is ΔE = 665 MWh, which represents 11.3% from the total consumption in 2006, respectively 16.5% from the consumption in the 8 months.

In fig. 14 is presented the graphic of the monthly consumptions in 2006 and 2007.

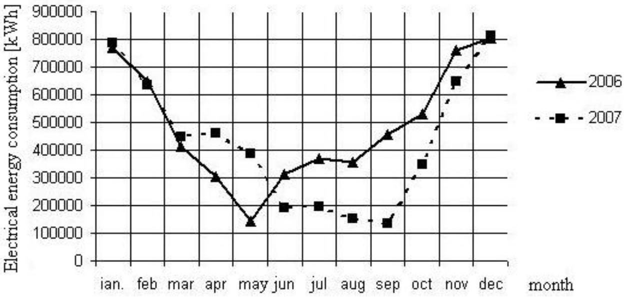

Fig.14. The system's electric power consumption in 2006 and 2007

Only by reducing the electric power consumption, the investment's depreciation is done in 3.5 ÷ 4 years. Moreover, the system is not subjected anymore to pressure variations depending on consumption, resulting important savings regarding the maintenance (pipe breaks) and also the motors' electric operation regime is much better (less defects).

The heat quantity vehicled in primary district heating circuit depends on the water flow, the water's specific heat c and output temperature T_T. The heat transfered to the secondary circuit has the expression:

$$\Delta C = m \cdot c \cdot \Delta T, \qquad (5)$$

where m is the mass of the water vehicled in the primary district heating circuit and

$$\Delta T = T_T - T_R \,, \qquad (6)$$

is the temperature difference between tour and retour. At a constant heat quantity ΔC transfered, it results that the product between mass and temperature difference is higher as the pumped water quantity is smaller.

Table 1

Measurements' results

Day	Temperature		Δp [barr]	Q [m^3/h]	P [kW]
	Tour [^{0}C]	Retour [^{0}C]			
1	80	64	7.2	720	250
2	78	63	7.2	768	272
3	76	62	7.2	822	290
4	74	60	7.2	823	291
5	72	59	7.2	886	315
6	70	57	7.2	886	315
7	68	55	7.2	886	315
8	66	54	7.2	960	340
9	64	53	7.2	1047	358
10	62	52	7.2	1152	376

At a higher temperature of the heat carrier at the entrance in the heat station, the opening of the heat exchanger's diaphragm is smaller and, in this way, decreases the pressure drop Δp_k on the heat station. Sumarizing these reductions from all the heating stations its reducing the the total pressure drop Δp from the circuit and it will reduce also the electric power consumption. This solution was experimented during the warm season, when the thermal energy consumption is approximately constant. The measurements' results taken on 10 days are presented in table 1.

Each value from the table represents an average of the recordings taken hour-by-hour during one day. One can observe that at an increase of the output temperature of the primary heat carrier by 18 ^{0}C, the vehicled flow is reducing by 36%, and the absorbed electric power by 34%. The consumption reduction is substantial, but this working mode could not be applied before the complete automation of the district heat system.

7 Conclusions

Introduction of variable-speed driving systems determines the reduction of the electric power consumption by minimizing the hidraulic losses (valves, diaphragms, etc.) and by improving the operation regimes. It was experimentally shown that the investment's recovery can be done in 2-3 years, without quantifying the economic effects of decreasing the maintenace costs which are not neglectable.

By the experience gained in designing, execution and operation of such system can be achieved many other applications with same benefic energetic effects, which finally can lead to important economical results.

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