UNIVERSITY OF CRAIOVA
THE FACULTY OF ELECTRIC ENGINEERING

PH.D THESIS
ABSTRACT

THE MULTIFUNCTIONAL STATIC SYSTEM WITH APPLICATIONS IN THE MAINTENANCE OF HYDROPOWER EQUIPMENTS

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INTRODUCTION

My motivation to go through the doctoral training stage was mainly the desire to improve myself on a direction that is useful in my coordinating work of a collective that work in the maintenance of hydropower equipment. The theme of the thesis was established in the summer of 2011 when I had a dedicated discussion to Mr. prof. Dr. Ing. Alexander Bitoleanu. On this occasion I found out about a project proposal, funded from structural funds, drawn up by him and prof. eng. Mihaela Popescu, had just been declared eligible with a very good score. In this context, he came to meet my option and I was asked to identify a theme that would interfere with the topic of the project. We analyzed the technological processes that use the heating in the section that I was coordinating, and we concluded that in order to have a high degree of flexibility is required multifunctional static system that can provide both d. c. energy as well as the a.c. power, and at the same time, to enable adjusting the frequency and the power level. After two weeks, the theme has been finalized as "**The multifunctional static system with applications in the maintenance of hydropower equipment**." The objectives set were:

1. The identification of some structures of static systems which use heating induction and at the same time, to enable the adjusting of voltage / of frequency and of the power level.
2. The modeling of these structures, the determination of the energy performance and the establishment of more favorable structures.
3. The design of the chosen structure.
4. The acquisition of such a system, commissioning and experimental verifications.

Accordingly, after my admission to Ph.D. I became a member of the research team of the project "A System for induction heating with high_1 energy efficiency" project POS CCE, Operation 2.1.1: Research projects in partnership between universities / research and development institutes and businesses, the beneficiary being SC INDAELTRAC Ltd., No. 258 / 28.12.2011.

At the request of the beneficiary, the project was targeted to design, to analysis and to implement an experimental model system for induction heating with high energy efficiency for heating the final long pipes in the rolling process.

The project finished, according to provisions at the end of 2013 and all the targets set were fulfilled.

As a member of the research team I have participated only in some stages established by the management team of the project, and elements of these steps are found in my thesis.

I must point out, with regrets, that the work of achieving this thesis was heavily disrupted by the insolvency of S.C. Hidroelectrica SA and reorganizations that followed. There were two direct consequences:

1. The interruption of my traineeship for two years;
2. The impossibility of acquiring the system designed and analyzed in this thesis.

Obviously, the 2nd consequence led to the failure of the last objective of my thesis.

After an analysis carried out by the scientific coordinator at the beginning of 2016, he decided to replace the last objective with another two:

4.1. Experimental measurements to calculate the equivalent parameters related to the applications of heating from CHE Lotru;

4.2. Determination of the energy performances for the applications from the portfolio of the maintenance department at CHE Lotru.

The justification of the theme

In establishing the thesis my own motivation, as I specified above, was the starting point.

In exploiting the transformers of measuring and of the electrical machinery which equips the exhaust stations of the energy produced by the hydro power plant the need of drying them appears, either due to the wetting of the windings insulation or after being repaired, and in this case the winding or insulation is totally or partially replaced. The wetting of the insulation may be caused by loss of tightness between the components marks and the penetration of the air moisture and it is favored in the case of transformers, by the fact that the electrical insulating oil is hygroscopic.

Through the norm of tests and measurements on equipment and electrical installations, PE116 / 94 is required, for example, that for the current transformers which operate at voltages from 110kV-400kV, the value of the insulation resistance should be greater than 5000 MΩ . Otherwise, otherwise it cannot be put under voltage.

The drying of the coil can be performed in different ways: by external heating, by heating with current from an independent source, heating through short circuit current, through venting, through losses of the active iron in the body of the equipment. In cases where, through a certain method fails to achieve the required drying temperature or when the heating of the different parts is not uniform, the combined drying method is used, which consists in combining the two methods.

Currently, at Hidroserv Ramnicu Valcea, the drying of the transformers used in the transformation stations of great power is made by combining the heating through induction at a frequency of 50 Hz with heating through conduction.

It is obvious, and the energy analysis that was done demonstrates this thing that the solution used is technically and morally outdated.

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Meanwhile, the scientific background and the existing methods of investigation have argued the opportunity of the theme set.

A modern and efficient heating method is to use a time-varying electromagnetic field. In the volume of the metal piece, eddy currents are induced, whose distribution depends on the geometry of the piece and the material properties, and also on the frequency of the electromagnetic field. The higher the frequency is with that much the Joule losses due to eddy currents mainly are mainly distributed in a narrower area, located right next to the surface of the area. Basically, at the heating of the metal parts contributes the losses due to hysteresis loop. Heating through induction has several important advantages: practically non-existent pollution, a good repeatability, thickness adjustment of the heated layer, relatively easy automation etc. These advantages justify the widespread use of this technique in many establishments producing laminated tubes. It is interesting to note that steel loses magnetic properties when heated above about 700 ° C. This temperature is known as the Curie temperature. This means that above 700 ° C does not produce a heating of the material due to hysteresis loss. Any heating above this temperature should be ensured only by eddy currents. This makes steel heating above 700 ° C to be a challenge for heating systems through induction.

While the principle of heating through induction is known for a long time, items related to industrial research, enabling implementation of the method with high energy efficiency, are a trade secret or protected through a patent.

Considering the technological processes at Hidroserv Râmnicu Valcea, which use heating to have a high degree of flexibility, a multifunctional static system is required that can provide both c.c. energy as well as the a.c. power, and at the same time, to enable adjusting the frequency and the power level. This may include a semi controlled or ordered rectifier, in a single-phase bridge inverter and a voltage bipolar transistors with isolated base (IGBT) capable of operating with a resonant load.

It is estimated that induction heating is practically mandatory in the case of mounting through pressing of mechanical components and of dismantling them.

The content of the thesis in relation to the objectives set

The thesis is divided into 8 chapters, an introduction and conclusions.

Chapter I is divided into four subchapters and dealing with the theoretical part necessary to achieve the objectives of the thesis.

I.1.Theoretical aspects of induction heating.

I.2. Features regarding the induction heating of the long pipes.

I.3. The influence of the work frequency.

I.4. Technological processes based on heating, in the maintenance of hydropower equipments.

The electro-thermal aspects of the induction heating process presented in § I.1, I.2 and I.4 are taken from specialized literature (especially in [12], [69] and [18]), the author of the thesis bringing minor contributions and systematizing and apply an algorithm in a useful form.

Thus, after identifying specific technological requirements and elements, it was elaborated an algorithm to calculate the power and the characteristic electrical quantities for both the voltage inverter and the current inverter.

Further, the analysis of the impact of work frequency, based on the developed algorithm, revealed the following that the increasing of the frequency above the resonance determines the decreases of the penetration depth but it has a positive impact on the energy performance.

The equation (1.52) shows that when frequency drops below the value of the resonance to keep constant the output power, current must be increased because:

1. It is inverse proportional to f1 / 4; for example, a 20% reduction of the frequency increases the current by 1,057 times;

2. It is inverse proportional to the coefficient F, which can dramatically lower the frequency; For example, if the resonance $d / \delta = 4$, a 20% reduction in the frequency increases the current to 1.14 times.

It follows a totally increase of current of 1,205 meaning more than 20%. This growth will be found in greater proportion due to the netting of the reactive component in the current drawn from the inverter and the network.

In the end of the chapter, the technological processes based on heating from Hidroserv Râmnicu Vâlcea are presented, for the maintenance of hydropower equipment, namely: the drying of electric machines; the drying of transformers; the removing of the joints formed by pressing.

Chapter II is divided into three subchapters and deals with the first objective of the thesis.

II.1.The structure of the induction heating systems

II.2.The frequency of resonance of the equivalent load

II.3.The requirements of the power supply with resonant circuit

§ II.1 is an overview of the structure of the systems with current and voltage inverters, made by the author, based on specialized literature. Two conclusions can be drawn:

1. From historical point of view the performance of the voltage source inverter has been ignored due to poor adjustment of the active power transmitted to the load, the need to use the thyristors for small locks and fast power diodes.

2. By constantly improving the performance of thyristors and the spectacular growth of bipolar transistors with isolated base (IGBT) became appropriate the performance reconsideration of these inverters [5], [20]. It is why, in this study will be considered for analysis, two types of inverters made with IGBTs.

§ II.2 is the contribution of the research team where the doctoral student was part of. Thus, starting from the fact that the coil equals to the load, is composed of the coil of induction and the body to be heated and, accordingly, it has a resistance which cannot be neglected, the expression of the frequency of resonance existing in the literature is deducted, only by using the phasor diagrams.

The chapter ends with the synthesizing of the requirements of power supply with resonant circuit. It concludes that the power supply should provide:

1) Constant output power;
2) The voltage applied to the capacitor is limited;
3) Limited load current;
4) The effective operation.

It also points out that, after consulting the representative bibliography, it was decided a detailed analysis of the two variants of the induction heating system of pipes with high energy efficiency.

1) The induction heating system with voltage inverter with amplitude modulation, bipolar base isolated (IGBT) and parallel resonance.

2) The induction heating system with current inverter, with amplitude modulation, bipolar base isolated (IGBT) and parallel resonance.

Chapter III is devoted to the influence analysis of temperature and of harmonics on the parameters and on the energy performance and brings elements for achieving the first objective of the thesis. The analysis was done in Excel with a program that uses the relations from chapter I.

Thus, the first part entitled "The influence of temperature on the parameters and the energy performance " refers to the heating of a pipe with an external diameter of 0,076m, using the same type of inductor in two distinct situations:

- at an average temperature above the Curie: 950C (Case 1);
- at a average temperature below the Curie: 350C (Case 2).

The major findings resulting from the analysis of the numerical values obtained are shown below.

1. Only a few values are higher in case 2, respectively:

- the depth of penetration in the conductors of the inductor, more than 4.5 times; cause the decrease of the frequency of resonance of nearly 20 times;
- the time needed to pass through the 5 inductors, over 16 times;
- the power factor at the terminal of the inductor, more than 2.7 times.

2. Most values are lower or much lower. Of these:

-the frequency of resonance, almost 20 times; the main cause is the increase of the relative magnetic permeability, 10 times;

- reported values of the resistance and of the pipe reactance, more than 37 times;
- equivalent reactance to approx. 18 times;
- the output of an inductor, more than 50 times;
- the current drawn by an inductor, almost 3 times;
- the voltage on an inductor, nearly 50 times;
- the reactive power of the inductor, over 135 times;
- the active power of the inductor, nearly 50 times;
- the apparent power of the inductor, approx. 135 times.

It follows that the same converter, delivering at the output the same active current of approx. 500A (rated current), when heating the same pipe but below the Curie point (Case 2), as compared to heating above the Curie point (Case 1), makes energy performance much weaker, namely:

1. the increase of the temperature is only 500C to 1100C;
2. the productivity is approx. 16 times lower (rate ratio).

It follows that there is no static voltage and frequency converter which can be used with the same good energy performances, in any application of heating through induction.

§ III.2.The influence of harmonics on the parameters and the energy performance has in view the supplying form from a single-phase inverter for which the dead time is neglected and using the expansion of voltage in Fourier series.

The influence is analyzed using a numerical example for which energy parameters and sizes on harmonic calculate. It is mentioned that:

- it was taken into account the first six harmonics (n = 1, 3, 5, 7, 9, 11);
- the adaptation circuit is neglected;
- the inductor is a coil d1 = 0.168 m h 1 = 0.95 m, N = 26 turns;
- fundamental frequency is fr = 6947 Hz;
- the heated body is a carbon steel0.8% tube with the outer diameter d2ext = 0.128 m, wall thickness = 6.5 mm, length 15 m and speed v = 0.5 m / s;
-for the calculations the relations in Chapter I were used and from the calculation algorithm of powers (for powers).

After analyzing the results the following conclusions are drawn:

1. Although the distortion of the voltage provided by the inverter is approx. 50%, the distortion of the current through the inductor is only 7.9%;
2. In real terms, when between the inverter and inductor there is an adjustment circuit, the distortion of the current through inductor is less;
3. 97% of the transmitted power to the pipe is achieved on the current.

The final conclusion is that taking account of the fundamental harmonic in theoretical reasoning and the deduction of some calculations relations is justified and very close to reality. Moreover, the calculation is covered because there is a reserve of power that is transferred to the higher harmonics.

The last subchapter deals with the influence of harmonicon the frequency of resonance. To explore this issue, it was conducted the model of the inverter system of voltage - adaptation circuit inductive -inductor-pipe - compensation capacitor in Matlab Simulink environment.

Then it was calculated the actual amount of current flowing in the inverter to control multiple frequencies located around the frequency of resonance of the equivalent circuit.

It was noted that the frequency at which the operation of resonance takes place (which minimizes the RMS current given by the inverter) is higher than the frequency of resonance of the equivalent circuit inductor-pipe parallel to the compensation condenser (7.05kHz to 7.015kHz) .

CAP. IV. Experimental measurements to calculate the equivalent parameters related to the heating applications from CHE Lotru and this represent the support to fulfill the objective 4.1.

It contains four subchapters, namely:

IV.1. Experimental structure;

IV.2. Waveform and harmonic analysis;

IV.3. Energy analysis;

IV.4. The parameters of the equivalent load ;

IV.5.Conclusions.

Considering that the current transformer of 110kV from Ciunget station is a typical load, experimental determinations associated with the drying process were performed.

To do this, the current transformer is covered with an insulating textile laminate film, on which a coil of a number of turns is made up. The obtained coil has the shape of a truncated cone having the diameters bases of 600mm, 400mm and height of 700mm.

The conductor used is made of flexible copper, class 5 according to SR EN 60228, stranded profile (0,51mm wire diameter) with an outer diameter of 15,8mm. The insulation of the conductor of 1.6 mm thick is from silicone rubber, resistant to 180 ° C.

The power was made from the autotransformer to a source of D.C. welding capable of providing 1000A. They made two coil structures:

1. Coil with 33 turns for the effective values of voltage and current of 150A respectively 59V;

2. Coil with 38 turns for the effective values of voltage and current of 130A respectively 56V.

For each of the two structures were registered the current and voltage at the terminal of the equivalent coil, using a Tektronix TDS3000 oscilloscope. The current was recorded through a shunt of 5mΩ / 60mV, precision class 0,02%, frequency of acquisition being of 100kHz.

The Current waveform, obtained from the data acquired, contains high frequency harmonics. Their presence is due to the measurement shunt where voltages due to existing electromagnetic disturbances in the external environment are induced as well as to the sensitivity of the oscilloscope. For later use in the calculation of the parameters, the waveform was filtered with a first-order filter having the cutoff frequency of 10kHz, which eliminated the higher harmonics.

If the filtered waveform of the current is considered, the total factor of harmonic distortion is 3.8% and partial factor of harmonic distortion corresponding to the first 31 harmonics is 2.54%, slightly lower than the one corresponding to the unfiltered wave. It follows that the filtering process does not affect the low harmonics, with impact on energy issues

For the complete analysis of the energy were calculated the active power (P) and apparent (S) and Global Power factor (PF).

Numeric data shows that energy performances are reduced. Thus, the overall power factor has low levels approx. 38% for the coil with 33 turns and approx. 45% in the case of the coil with 38 turns.

If it is obvious that the drying process through heating the current transformer is more effective if the coil better covers its height and the number of the turns of the coil is higher, the energetic performances are better doing so.

One size that supports the search for new sources and technologies for drying through heating the current transformers, and of other components from hydro power plants is the power that can be compensated. For the analyzed cases, the power that can be compensated with favorable consequences on the supply system is approx. (2-2.5) the output power.

The equivalent load, comprised of the realized coil and current transformer as a heated body, is assimilated by an R-L circuit. In order to determine the two parameters we can work in two ways.

M1. It approximates the regime as being sinusoidal and filtered waveforms are used.

M2. It approximates the regime as being sinusoidal and relations inferred from power are used in two versions: a) using raw waveforms; b) using filtered waveforms.

Compared to the case of M1, the errors from M2 are of less than 1%, and the errors made in cases M2A) and M2b) as compared to the case I are less than 2% for strength, and less than 0.4% for the inductance. Consequently, it can be worked with any of the values of the resistance or of the inductance.

Chapter V is for the modeling of the multifunctional static system, in open circuit and contributes to achieving of the 2nd objective. The modeling in Matlab Simulink environment includes all the electrical components of the installation and is designed with elements from the SimPowerSystems library. Thus, there were obtained models for:

1. The heating system through induction with voltage inverter with bipolar transistors with isolated base (IGBT) and parallel resonance;

2. The heating system through induction with power inverter with bipolar transistors with isolated base (IGBT) and parallel resonance;

The parameters characteristic of the diode from the rectifier bloc respects the catalog values of the real rectifier diodes DD400S17K6CB2 manufactured by EUPEC, with the following main parameters from the catalog.

The model of the power inverters was also built as an independent block and it contains four IGBT transistors together with the four antiparallel diodes. Blocks have been added for the calculating of the dissipated powers by each transistor and of saving their values in the Matlab workspace.

The blocks of the transistors taken from the SimPowerSystems / Power Electronics library, have the values of the specific parameters set according to the data of the catalog of the FD800R17KE3-B2transistors, manufactured by Powerex.

One of the differences between the two models lies in the structure of the three-phase bridge rectifier, in the case of the static voltage and frequency converter with the role of a current source, is fully commissioned. This raises the need of a control block on the grid for the thyristors of the rectifier block. For simplicity, in this regard, it was used a control unit on a synchronized 6-Pulse Generator grid available in Simulink SymPowerSystems library/ Extra Library / Control Blocs. This block implements the principle of the phase command for the three-phase bridge rectifiers, with thyristors.

Chapter VI is dedicated to the estimation of the performance of the plant for heating the long pipes, in two established variants, fulfilling objective 2.

The performances were determined through simulation, using the models presented in Cap. V, and considering, as load, four sizes of pipes with the corresponding inductor and the compensation capacitor. The control frequency of the inverter was to the frequency of resonance of the equivalent inductor parallel to compensation capacitor. It was primarily aimed that on the basis of the performance analysis, to establish the most advantageous solution to design the main elements.

It is noted that to achieve results with high accuracy when using blocks of switch type (diodes, IGBT transistors etc), it was adopted a variable step of simulation by choosing a method of integrating of type ode15 or ode 23.

Being given the frequency of resonance of the oscillating inductor circuit - compensation capacitor, which can reach the value of 7 kHz, it was adopted a maximum simulation step of 1 μs, which is at least 100 times lower than the corresponding period of oscillation .

The main performances in the case of the installation with inverter current are:

1. The voltage across the inductor, the current through it and the current through the capacitor
are practically sinusoidal

2. The active power at the output of the inverter has a minimum value of 118 kW and a maximum value of 603 kW;

3. The efficiency depends both on the value of the current as well as the frequency of control and it has the minimal value of 0.692, respectively maximum value of 0.929;

4. The extreme values of the power efficiency are of 0.688, respectively of 0.905;

5. Extreme values of total efficiency are of 0.544, respectively of 0.738;

6. The power factor in the transformer secondary has extreme values of 0.78;

7. The maximum voltage that require the transistors is maximum at switching, it has important values, and the highest value is 3614 V, impermissible value.

For the plant of the power inverter, the main performances are:

1. The voltage across the inductor, the current through it and the current through the capacitor
are practically sinusoidal

2. The active power at the output of the inverter has a low value of 96.44 kW and a maximum value of 936.7 kW;

3. The efficiency of the converter depends on the amount of current and the frequency of control and it has minimum values of 89.77% and maximum values of 96.52%;

4. The extreme values of the electrical efficiency are of 88%, respectively of 95.5%;

5. The extreme values of the total efficiency are 61.6% and respectively 77.2%;

6. The power factor in the transformer secondary has extreme values 0.75, respectively 0.925;

7. The maximum voltage that require the transistors is maximum at switching, it has acceptable values and does not vary greatly from one pipe to another; There is practically no switching surge.

From the comparative analysis of the corresponding performances the two types of installation revealed the following:

1. The efficiency of the voltage converter is always greater; the greatest difference is 25 percent, and the lowest approx. 2 percent;

2. The power efficiency in the case of the voltage inverter is always higher;

3. The total efficiency in the case of the voltage inverter is always higher;

4. The tension request of the transistors is lower in the case of the voltage inverter;

5. The losses in transistors are lower in the case of the power inverter;

6. The total power factor is higher in the case of the voltage inverter;

7. The total factor of harmonic distortion of the current through the inverter is always lower in the case of the voltage inverter.

In conclusion, the solution that was considered for designing the main elements of the force part, was the parallel resonant voltage inverter.

In Chapter VII it was achieved the design of the force part of the multifunctional static system with applications in the maintenance of the hydropower equipment based on parallel resonant voltage inverter but powered by a semicontrolled three-phase bridge rectifier. This chapter answers to the 3rd objective of the thesis.

Starting from the technological processes that use the heating and the requirement as system to better meet the needs, its structure was set up, and based on the doctoral candidate experience, technical characteristics have been established.

Having in view the energy performances determined using the Simulink models, the multifunction static system will consist of:

1. semicontrolled phase bridge rectifier;
2. single-phase voltage inverter with bipolar transistors with isolated base (IGBT) capable of operating with a resonant load.

The multifunctional character of the rectifier-inverter system will be ensured through:

1. The ability of the semicontrolled rectifier to work as an independent source. In this way, between the rectifier and inverter a contactor will be provided with accessible input terminals (from the rectifier) ;
2. The capacity of the system to work as static voltage and frequency converter with variable frequency in a wide field;
3. The capacity of the system to work as static voltage and resonant frequency converter with resonant load;
4. The capacity of the system to power a wide variety of resonant specific tasks to the shown processes in §I.4.2-I.4.5.

It was considered that the power of the converter is done from the source of 3x380V, existing at Hidroserv Lotru.

First, it has been analyzed and dimensioned the optimal adaptation coil so as to maximize the fundamental harmonic of the current through the equivalent inductor, then they were sized and chosen:

1. IGBT modules with antiparallel diodes;
2. The capacitor from the intermediate circuit;
3. The thyristor and the diodes of the rectifier.

Through the IGBT modules, the diodes and the thyristors of the rectifier, the cooling bodies on the basis of the checking at heating in stationary regime were chosen and dimensioned.

They also calculated, the protection circuitry at surge related to the IGBT modules and to the diodes and to the compensation capacitor.

Chapter VIII covers the performance estimation of the multifunctional static system for the maintenance of the hydropower equipment, fulfilling *the objective of the thesis 4.2*.

The performances were determined through simulation, based on the models presented in Chapter. V, which were made in accordance with the structure and the parameters obtained in chapter VII. There were considered two structures of the three-phase rectifier in bridge: semicontrolled and fully commissioned. They have updated the values of all parameters, as obtained through the calculations of the design. As a load, the current transformer with inductor and the corresponding compensation capacitor. The simulation targeted the operation in open circuit to determine the performances and achieving the switching to zero current.

To obtain results with high accuracy as close to reality, it was adopted a constant step of simulation by choosing a method of integration of type ode3 Bogacki-Sampine for discrete systems.

Being given the frequency of resonance of the oscillating circuit inductor - compensation capacitor, of maximum 3 kHz, it adopted a maximum simulation step of 1 μs, which is over 300 times lower than the control period.

It was simulated the functioning in the case of the drying operation of the current transformer in the two versions of the inductor (33 turns and 38 turns) for the same active power of the equivalent inductor (approx. 15 kW) with a system equipped with a semicontrolled rectifier and completely ordered rectifier.

For all the eight structures of the system, it was analyzed the functioning for the two values of the control frequency of the inverter: the resonant frequency of the equivalent inductor in parallel with the compensation capacitor and the frequency for which the switching is obtained corresponding to the current close to zero.

In the case of the semicontrolled rectifier system, from the analysis of the numerical results and of waveforms, the following are mentioned:

1. The voltage in the secondary of the transformer is very little affected by rectifier commutations, the current is rectangular and wavy, and its shape depends on the angle control;

2. The voltage from theintermediate circuit of c.c. is practically constant and the current is pulsed;

3. The output voltage of the inverter is rectangular, and the current is symmetrical and sinusoidal;

4. The voltage across the inductor, the current through it and the current through capacitor are practically sinusoidal.

Regarding the influence of the control frequency of the inverter, respectively the one corresponding to the resonance and the one that ensures switching to zero current, shows the following:

1. To achieve the same active power in the equivalent inductor, the continuous voltage at the input of the inverter is with approx. 200V lower in the case of the switching to zero current;

2. The voltage in the secondary of the transformer is symmetric in the case of the commutation to zero current and strongly asymmetrical to the resonance;

3. At resonance, the voltage at the entry of the inverter has negative values showing that for short intervals, the filtering capacitor is charging from the load, too;

4. At resonance, the switching of the inverter occurs at maximum flow;

5. In the case of switching to zero current, the equivalent inductor has a capacitive nature illustrated by the higher current flow through the compensation capacitor;

6. The efficiency of the rectifier and of the inductor are practically constant at the switching of the control frequency of the inverter and have high values;

7. The efficiency of the inverter and the overall efficiency depends significantly on the control frequency;

8. The total efficiency is approx. 4 percent higher for the zero current switching;

In the case of the system of the fully controlled rectifier, the numerical results correlated with the graphics outcomes enable highlighting specific issues.

1. The voltage in the secondary of the transformer is affected by the commutations of the rectifier and the current is rectangular and wavy.

2. The voltage from the main circuit of c.c. is practically constant and the current is pulsed.

3. The voltage at the output of the inverter is rectangular, and the current is symmetrical and sinusoidal.

4. The voltage across the inductor, the current through it and the current through the capacitor are practically sinusoidal.

The control frequency of the inverter, respectively the one corresponding to the resonance and the one that ensures switching to zero current, has the following effects:

1. To achieve the same active power in the equivalent inductor, the continuous voltage at the input of the inverter is over 100V lower in the zero current switching;

2. The current in the secondary of the transformer is practically symmetrical;

3. At resonance, the current at the inverter input has negative values showing that for short intervals, the filtering capacitor is charging from the load, too;

4. At resonance, the switching of the inverter occurs at maximum flow;

5. In the case of the zero current switching, the equivalent inductor has a capacitive nature illustrated by the higher current flow through the compensation capacitor;

6. The efficiency of the rectifier and of the equivalent inductor are practically constant at the switching of the control frequency of the inverter and have high values;

7. The efficiency of the inverter and the overall efficiency depend significantly on the control frequency (Tab. VIII.3, Fig. VIII.10);

8. The total efficiency is approx. 4 percent higher when switching to zero current.

Comparing the results obtained when using the two types of rectifiers at the order of the frequency inverter that provides switching to zero current, for both types of coil, it appears that energy performance are similar and cannot be a criterion to establish better options.

The only criterion is the price, and this justifies the adopted approach in the design or respectively of using a semicontrolled rectifier.

Having in view the content of the thesis, synthesized above, I consider that the objectives were fully achieved at an appropriate scientific level, too.

Dissemination of the results

The results obtained in this study have been released so far through three works

1. Energetic Analysis of Drying Process of Current Transformer from 110 kV Ciungetu Power Station, autori Dinu Roxan C. Doboşeriu, Alexandru Bitoleanu și Mihaela Popescu, in process of publication in the magazine Annals of the University of Craiova, Electrical Engineering series, ISSN 1842-4805, nr. 40/2016, (indexare Index Copernicus) – in process of publication.
2. Energetic Performances of an Induction Heating System with Half-Controlled Rectifier Destined for Drying of Current Transformers from 110 kV Ciungetu Power Station, authors Dinu Roxan C. Doboşeriu, Alexandru Bitoleanu și Mihaela Popescu, Proceedings of 13th International Conference on Applied and Theoretical Electricity (ICATE), Craiova, ROMANIA, 6-8 Oct., 2016, (indexare ISI Proceedings) – in process of publication.

3. Modeling and Performances of an Induction Heating System with Resonant Voltage Inverter for Drying of Current Transformers from Ciungetu Power Station, authors Dinu Roxan C. Doboşeriu, Alexandru Bitoleanu și Mihaela Popescu, the 18th National Conference of Electic Actions 2016, 13 - 14 octomber 2016, in process of publishing in magazine Acta Electrotehnica (CNCSIS B+).

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CONCLUSIONS

The preparation and the elaboration of the thesis involved the following steps:

1. Establishing the theme.
2. Drawing up the individual program of advance training.
3. Going through the stages mentioned in the individual program of advance training.
4. Preparation of individual research program and formulating a concrete theme.
5. Defining the objectives of the thesis.
6. Going through the steps mentioned in the research program.
7. Systematization of the obtained material from research and the development of the thesis.

It was appreciated that the conducted research had three main features:

1. It was ascertaining because the doctoral student documented on the process of heating through induction, with emphasis on the modern equipment used;
2. It was extensive because the employing of this process in the field of hydropower equipment maintenance was followed;
3. It was intense because it offers explanations about the characteristics of the necessary equipment and energy performance in the field of hydropower equipment maintenance.

It is estimated that in the conduct of research, the doctoral candidate used appropriate research methods to achieve the targets set. Of these, the following are stated:

1. Observing and measuring the phenomena and recording the specific physical quantities of the research topic;
2. Development and ordering of the material;
3. Identification of possible structures of equipment and creation of suitable models for the investigation of their performances;
4. Designing a multifunction equipment for the maintenance of hydropower equipment
5. Testing of equipment on the model based on data obtained from experiments;
6. Confirmation of the expected performance;
7. Publication of the results.

Further, it will be detailed how the thesis is achieved, on chapters, and where appropriate, it will be highlighted the results achieved through the major contribution of the doctoral student.

Thus, **Chapter I** represents the theoretical foundation necessary to achieve the objectives of the thesis, and the electro-thermal aspects of heating through induction set out in § I.1, I.2 and I.4 are taken from literature (especially in [12], [69] and [18]) the author of the thesis bringing some minor contributions, systematizing and applying an algorithm in a useful form.

The content of subchapter I.3 is a substantial contribution of the author through,
I.1. Showing the influence of the control frequency of the inverter with respect to the resonant frequency, on the energy performance, at the precision heating of long pipes.

Chapter II contributes to the achievement of the first objective of the thesis.

§ II.1 is an overview regarding the structure of systems with current and voltage inverters, made by the author based on literature.

§ II.2 is the contribution of the research team the doctoral student was part of. Thus, starting from the fact that the coil equal to the load is composed of the induction coil and the body to be heated and, accordingly, it has a resistance which cannot be neglected, it is inferred the expression of the resonant frequency existing in the specialized literature, but using the phasor diagrams.

Chapter III, dedicated to the harmonic and temperature analysis on the parameters and energy performance and it completes the implementation of the first objective of the thesis.

The content is the contribution of the research team the doctoral student was part of and the results of his work are:

III.1. Excel application and interpretation of the results regarding the effect of temperature on the parameters and the energy performance to heat a pipe with an outside diameter of 0,076m using the same type of inductor, in two distinct situations, namely at an average temperature above the Curie level (950C) and an average temperature below the Curie level (350C);

III.2. Excel application and interpretation of results regarding the influence of the harmonics of the performance and energy performance of heating a pipe outside diameter of 0,168m;

III.3. Highlighting the influence of harmonic on the frequency of resonance on the model of the inverter system of voltage-adjustment circuit inductive -inductor-pipe-compensation capacitor in Matlab Simulink environment.

Chapter IV is the support of fulfilling the objective 4.1., it represents the doctoral student contribution:

IV.1. Experimental determinations relating to the drying process of the current transformer from the station Ciunget of 110kV, in the current technology, for the two coils (33 and 38 turns);

IV.2. The processing of the current waveform, obtained from the data acquired, by filtering with a first-order filter with the cutoff frequency of 10kHz, which eliminated the higher harmonics, for later use in the calculation of the parameters;

IV.3. Achieving of the complete energy analysis by calculating the active power (P), apparent (S) and can be compensated and of the overall power factor (PF);

IV.4. Determination of the parameters of the equivalent load composed of the produced coil and the current transformer as a warmed body (RL) in two ways (approximating the regime as being sinusoidal and using waveforms filtered and approximating the regime as being sinusoidal and using the relationships inferred from power, in two versions).

Chapter V, is the contribution of the research team the doctoral student was part of, contributes to the achievement of the 2nd goal and the results of his concerns refers to,
V.1. Achieving the patterns of force part, some blocks of computing and connecting them with the models of the control part.

Chapter VI is dedicated to the estimation of the plant performance in the case of heating the long pipes, in two versions, and represents the fulfillment of objective 2 and it is the doctoral student contribution materialized through:

VI.1. Determination by simulation on the model, of the performance of the system heating through induction with power inverter, four pipe sizes, with inductor and the related compensation capacitor at the command of the resonant frequency inverter of the equivalent inductor with compensation capacitor;

VI.2. Determination by simulation on the model, of the performance of the system heating through induction with voltage inverter, four pipe sizes, with inductor and the related compensation capacitor at the command of the resonant frequency inverter of the equivalent inductor with compensation capacitor;

VI.3. Comparative analysis of the performance corresponding to the two types of systems and identify the best variant respectively, the voltage inverter with parallel resonance.

In Chapter VII it was achieved the design of the force part of the multifunction static system with applications in the maintenance of the hydropower equipment. This chapter answers to the 3rd objective of the thesis and it is the contribution of the doctoral student materialized by:

VII.1. Configuring the structure of the multifunction static system, given the technological processes at Hidroserv Ciungetu that use the heating and the energy performance determined on the base of the Simulink models;

VII.2. The dimensioning of the semicontrolled rectifier and of the intermediate circuit;

VII.3.The dimensioning of the voltage inverter with parallel resonant load and the compensation capacitor.

Chapter VIII covers the estimation of the performances of the multifunctional static system for the maintenance of the hydropower equipment, fulfilling the objective 4.2 of the thesis and it is the contribution of the doctoral student. The results are:

VIII.1.The determining of the energy performance of the inverter designed for drying the current transformer in the two versions of the inductor (33 turns and 38 turns) for the same active power of the equivalent inductor (approx. 15 kW) with a system equipped with a semicontrolled rectifier, for the two values of the control frequency of the inverter (the resonance frequency of the equivalent inductor in parallel with the compensation capacitor and the frequency that correspond to the switching to the zero current);

VIII.2. The determining of the energy performance of the inverter designed for drying the current transformer in the two versions of the inductor (33 turns and 38 turns) for the same active power of the equivalent inductor (approx. 15 kW) with a system equipped with a fully controlled rectifier, for the two values of the control frequency of the inverter (the resonance frequency of the equivalent inductor in parallel with the compensation capacitor and the frequency that correspond to the switching to the zero current);

VIII.3. Interpretation of the results for the eight variants and synthesizing the useful conclusions;

VIII.4.The comparative analysis of the results obtained when using both types of rectifier, at the command of the frequency inverter that provides switching to zero current for both types of coil and the validation of the solution designed.

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