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Experimental Results from Physical Model of Bidirectional Power Flow Regulator for Power Substations of Electrical Transport

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***Abstract* - This article is about model of bidirectional power flow regulator for power substations of electrical transport. The paper presents an experimental model which is made in the laboratory of Power and electrical engineering of Riga Technical University. Also principal block scheme and principal schemes of that model are presented in the form of computer modeling as well as some main results of experiments are presented in the form of diagrams.**

I. INTRODUCTION

After modernization of all tramcars in Riga a new vision [9] of possibility to save electrical energy of electrical system of electrical transport by returning recuperated energy generated by tramcars in braking regime appeared. New vision consisted of elaboration of new bidirectional power flow regulator what will be able to regulate power flow from DC line to AC line and otherwise. Therefore work of elaboration has started and four principal schemes of experimental model were developed in simulation program PSIM v.6.0. The modeling resulted in the decision to develop an experimental model of bidirectional power flow regulator especially according to the principal scheme [1] of 10th substation of electrical network of Riga (Fig.1).

Fig. 1. 10th substation of electrical network in city Riga.

II. PRINCIPAL SCHEME OF 10TH SUBSTATION

Nowadays in Riga all power substations that are providing electrical energy for trolleybuses and tramcars are equipped with electrical schemes [2] like that in Fig. 2.

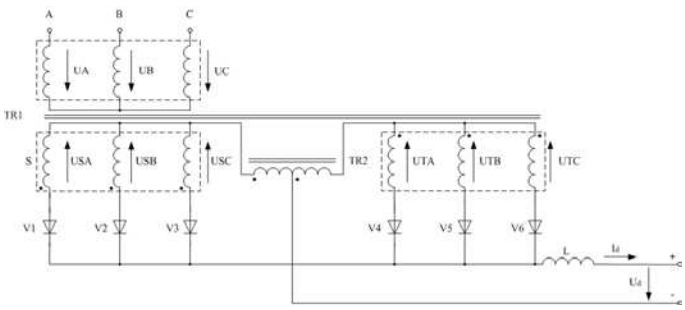

Fig. 2. Simplified electrical scheme of power substation.

The principal scheme [4] of that kind does not provide bidirectional energy flow from AC line to DC line and from DC line to AC. As we can see – this scheme provides only one way of power flow. In Fig. 2 we can see three phase six winding transformer which should be left unchanged because these transformers were installed lately. Under these conditions the decision to bring forward the aim to develop bidirectional power flow regulator according to Fig.3 was made.

III. BLOCK-SHEME OF BIDIRECTIONAL POWER FLOW REGULATOR

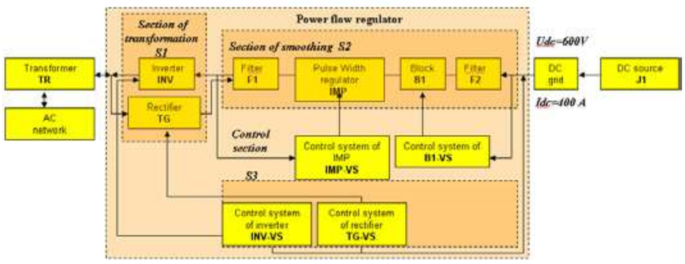

Fig. 3. Block-scheme of experimental bidirectional power flow regulator.

The block scheme of power flow regulator consists of three sections. **First section** called section of transformation consists of inverter and rectifier. The inverter and rectifier of the first section consist of IXYS [5] modules of thyristors MCC26-12IO8B – with the following electrical parameters: V_{RRM}=1200 V, I_{FRMS}=2x50 A, I_{FSM}=520 A V_{GT} =1,5 V, I_{GT} =100 mA, dv/dt = 100 V/us and with rated current 50 A. This kind of the rated value was chosen for safety and as bidirectional power flow regulator is at the first evolution stage where many unknown technical problems can occur in researching process.

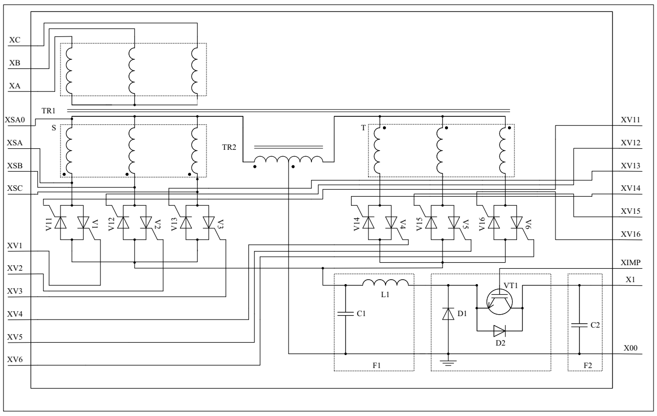

Fig. 4. Principal – power scheme of bidirectional power flow regulator.

After the experiments at this first evolution stage the suitable rated value of current and technical parameters of thyristors will be known. Totally there are planed three stages. The first stage is to make **experimental model** in laboratory for experimental researching, the second stage is to make experimental model in substation and the third stage is to make a prototype for production. In Fig.4 every thyristor is connected to drivers through optocouplers TO 125-12.5.

The second section called section of smoothing consists of filter F1 buck – up pulse regulator, block B1 and RC filter block F2. The **third section** called section of control consists of control systems for rectifier and inverter and control systems of pulse regulator and block B1. In this experimental model the control of drivers was realized by analog [8] microchips what was enough for that kind of experiments.

IV. RECTIFIER REGIME

As we saw before there were two main regimes for bidirectional power flow regulator. The first one is rectifier regime [6] and the second one is recuperative regime. In this article the rectifier and recuperative regimes are shown in stationary processes. In Fig.5 there is the principal scheme of bidirectional power flow controller simulated with simulation program PSIM v.06. The rectifier regime was simulated separately from the recuperative regime and in every simulation process the values of the resistors which were instead of load were changed. In this scheme three phases six winding transformer unit was used directly from the database of simulation program PSIM v.6.0 as well as smoothing transformer. In simulation of the rectifier regime also part of control system which is related to the rectifier regime was simulated. After simulation of the rectifier regime there many diagrams of currents and voltages of bidirectional power flow regulator were obtained and one of them is shown in Fig.6. These are the diagrams of current and voltage on the AC input of bidirectional power flow regulator. Actually in Fig. 6 the current is shown according to the acceptance that input voltage at the AC side is 800 V, therefore the value of current is approximately 150 A. Also we can see that simulation is made taking in account the looses of voltage. Fig.7 demonstrates the result of simulation for the experimental model where all virtual parameters correspond to physical parameters of the model. It means that input of voltage is not 800 V but 182 V also losses of voltage were taken into account and it is possible to see that the form of current is not rectangular.

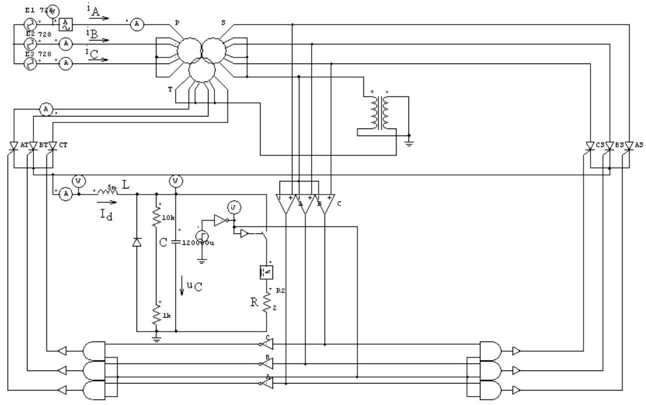

Fig. 5. Principal scheme of simulation of rectifier regime.

$$U_d = U_{d0} - \frac{3 I_d X_a}{4\pi}. \qquad (1)$$

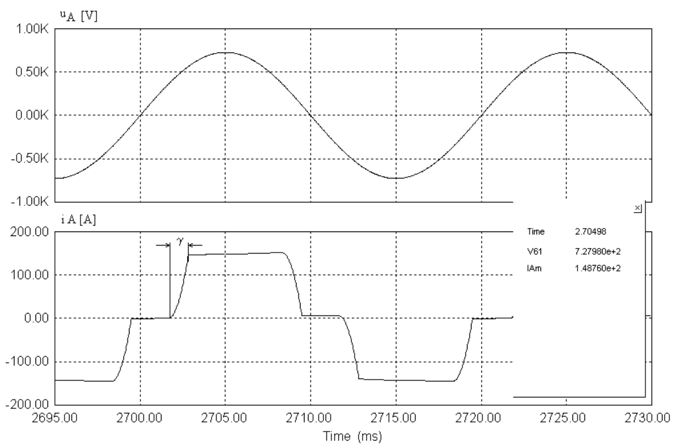

Fig. 6. Characteristics of current and voltage of bidirectional power flow regulator's simulation in rectifier regime in AC side

Fig. 8 presents the result of measurements of experimental model and if we compare it with simulation results then we can see that they are very similar to each other.

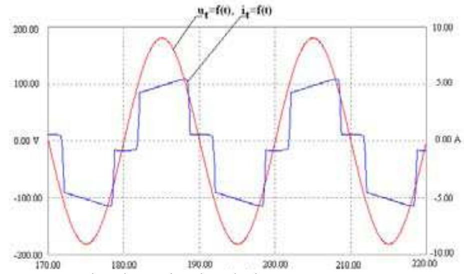

Fig. 7. AC current and voltage in simulation program PSIM 6.0

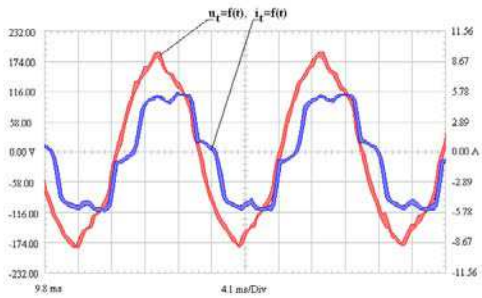

Fig. 8. Experimental measurements of rectifier regime.

V. INVERTER REGIME

Also during the experiments virtual model in simulation program PSIM 6.0 for inverter regime of bidirectional power flow regulator was created and the principal scheme of that virtual model is shown in Fig. 9.

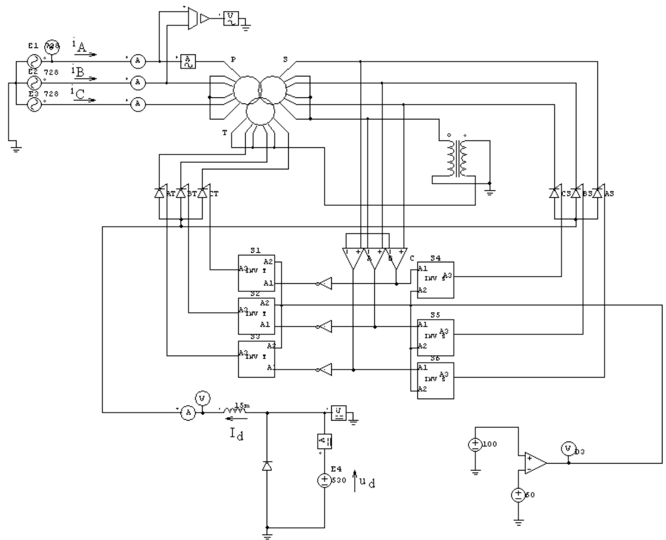

Fig. 9. Principal scheme of simulation of recuperation regime.

There are some parts of control block for inverter regime, too. In this virtual scheme a DC voltage source is used. Also simulations with DC current source were realized, because the drives of tram car in recuperative regime have characteristics more similar to current source than to voltage source.

$$U_d = -U_{d0}\cos\alpha + \frac{3I_dX_a}{2\pi} = 1.017U_{2f} + \frac{3I_dX_a}{2\pi} \,. \qquad (2)$$

$$I_{dmax} = 0{,}134\frac{\sqrt{6}\cdot U_{2f}}{X_a} = 602\ \text{A}\,. \qquad (3)$$

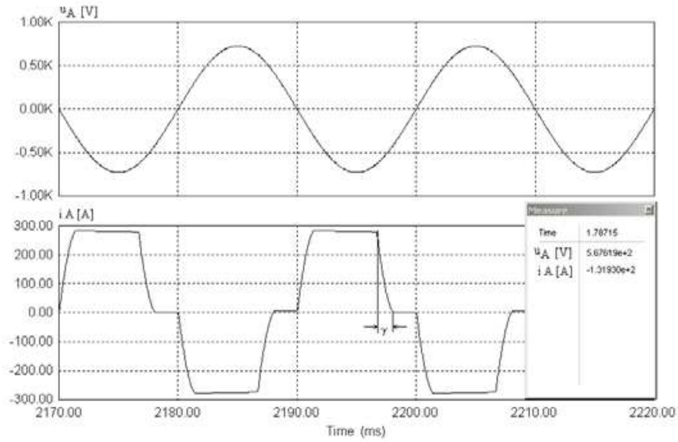

Fig. 10. Characteristics of current and voltage of bidirectional power flow regulator's simulation in recuperation regime in AC side.

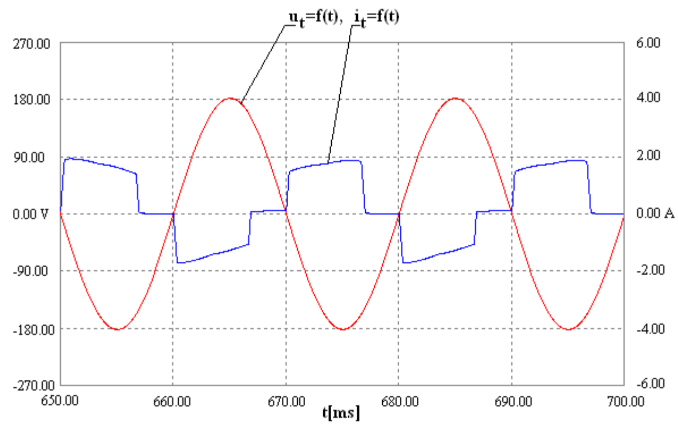

Fig. 11. AC current and voltage in simulation program PSIM 6.0

Fig.10 demonstrates the result of simulation with electrical parameters similar to real substation and Fig. 11 shows the result of simulation with electrical parameters of the experimental model. In both cases the results are similar, that means that experimental measurements must be the same. In Fig. 11 we can see that really experimental measurement on the experimental model is almost equal with simulations results. That means that the simulation scheme very pecisely describes the real experimental model and the processes in it. Fig. 11 and Fig. 12 show that the forms of current and voltage are very similar and theirs amplitudes too.

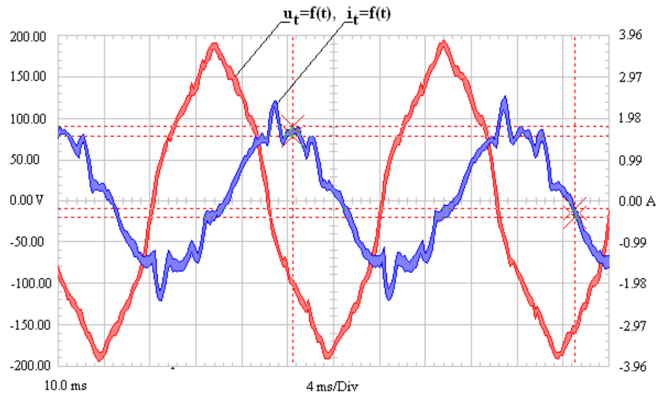

Fig. 12. Experimental measurements of recuperation regime.

VI. CHARACTERISTICS OF DC SIDE

Fig. 13 presents the characteristics of DC side in rectifier and inverter regimes for real substation when S = 600 kVA and input voltage of phase is 512 V. With these assumptions we got the following linear characteristics theoretically according to formulas (1), (2) and (3).

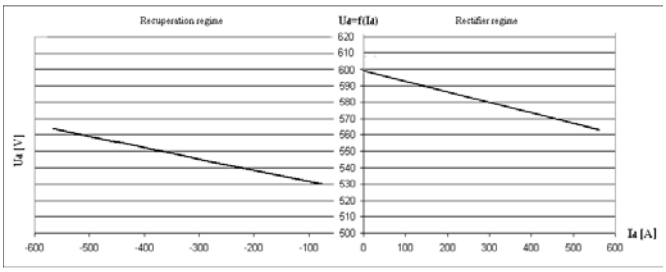

Fig.13. Characteristics of load in rectifier and recuperation regimes.

In Fig. 14 we can see characteristics of load of experimental model in rectifier regime. Actually there are three characteristics. Characteristic R was made when the experimental model was operated without smoothing filter and characteristic L was made when the experimental model was operated with smoothing filter L. There we can see that characteristic with filter L on DC side gives higher values of voltage Ud.

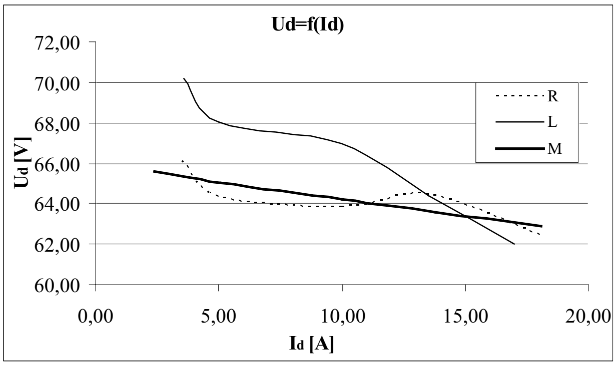

Fig. 14. Characteristics of load of experimental model in rectifier regime.

M is theoretical characteristic made by calculations according to formula (1) where argument is Id. We also can see that there are small oscillations of experimental characteristic R along theoretical characteristic M.

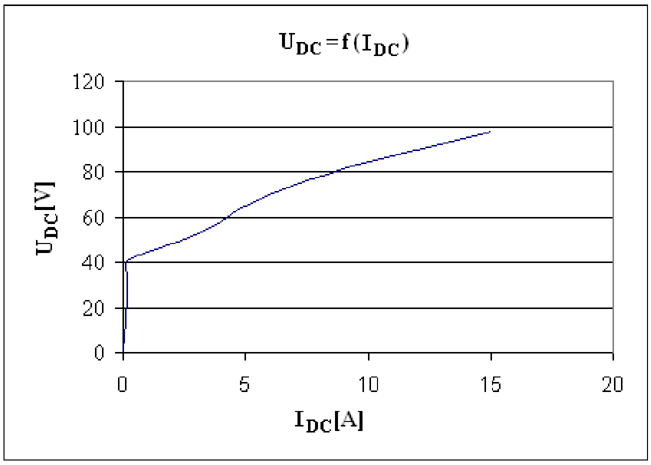

Fig. 15. Characteristics of DC source when M3 was used as DC voltage source.

In elaboration process of experimental model two physical experiments were realized. Firstly physical experimental model was explored when DC source was DC motor M1 according to Fig. 16 and secondly when DC source was rectifier of laboratory according to Fig 18. In the first case according to the experimental measurements we can see that characteristic of load is the same like that in Fig. 15 and Fig. 16. There is one imperfection in the second physical experiment because the DC source in the recuperation regime was taken form DC rectifier and its rated output voltage was lower than the voltage of DC drive in the second physical experiment. This imperfection leads us to Fig. 17 where we can see that the maximum of experimental current was 4.3 A. If we compare these characteristics by maximum current in physical experiment then we can see that in the first case it reached 15 A and in the second case only 4.3 A. In the next physical experiment we need to develop an additional DC source what will have the same value of power S like our bidirectional power flow regulator. Then it will be possible to reach higher value of transmitted current and power than in those two physical experiments.

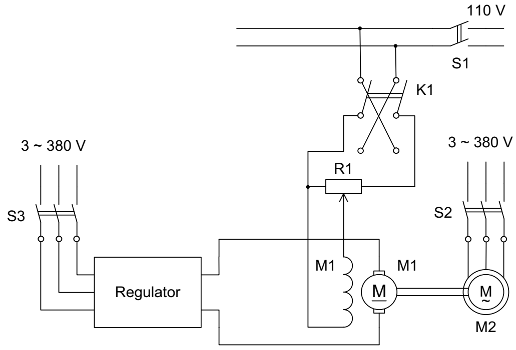

Fig. 16. Principal scheme when M1 was used as DC voltage source.

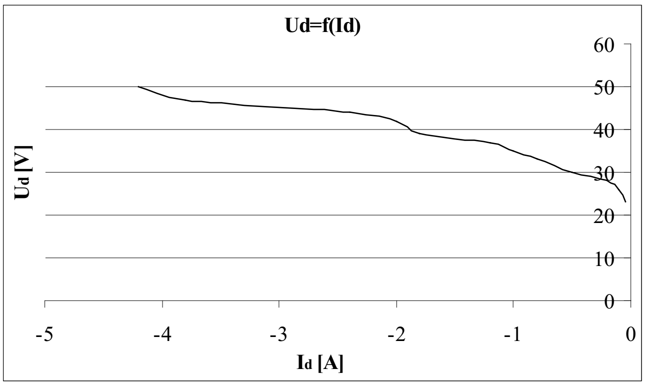

Fig. 17. Characteristics of DC source in recuperative regime (experimental)

VII. DESCRIPTION OF EXPERIMENTAL MODEL IN LABORATORY

In Fig. 18 we can see the experimental model of bidirectional power flow regulator which is tested in rectifier regime and recuperative regime. In the rectifier regime the regulators are connected to AC source and through three phase six winding transformer which is connected in star. After the transformer there are a power circuit made of thyristor modules, smoothing coil and load. In the experiments rheostat was used. In recuperation regime DC source – rectifier of laboratory is connected to inductance L in stead of load. Then the energy flows from DC source through regulator to AC source. All currents in all regimes were measured by oscilloscope Fluke SW90W and by Velleman pc scope. Also main impulses of control system in both regimes were received and saved in computer for further analysis. Control system of tyristors is made in this case by analog micro schemes because of cheapness but in further elaboration stage a digital microchip was used which will generate all control signals for drivers of thyristors.

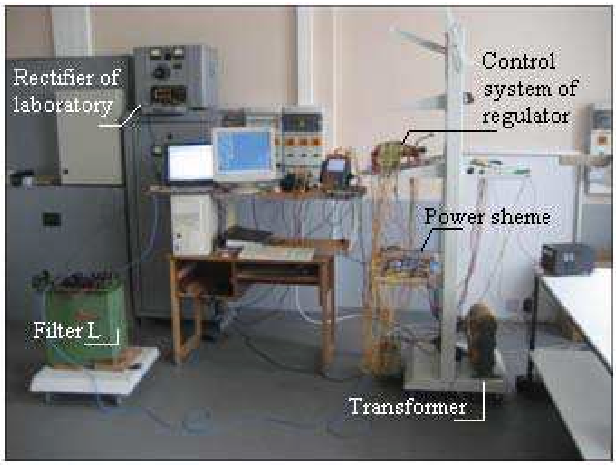

Fig. 18. Photo of experimental model in laboratory.

VIII. ANALYSIS OF ENERGETICAL PARAMETERS

After physical experiments and measurements many data were obtained and most important data are presented in this manuscript. Fig.19 presents a diagram of power vectors. It shows how much power was transmitted through the experimental bidirectional power flow regulator in laboratory. We can see in Fig.19 that maximal power S = 503 VA, P = 452 W and Q = 221 VAr were transmitted in the rectifier regime and S = 160 VA, P = -46 W and Q = 156 VAr in the recuperative regime. These results were got from the experiment when DC source was the rectifier of laboratory. That kind of data was not registered in the first experiment when DC drive was used as a DC source.

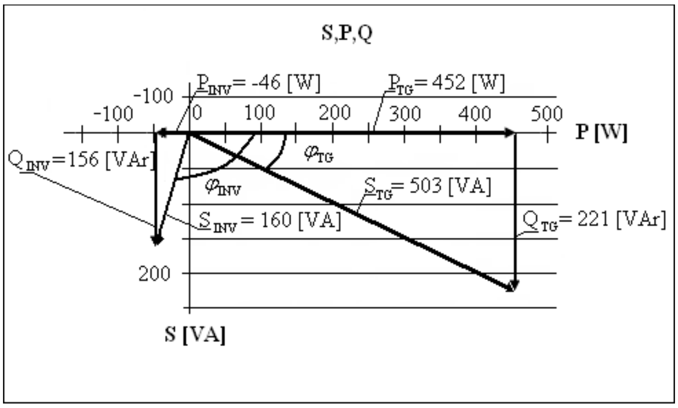

Fig. 19. Diagram of power vectors.

Fig. 20 shows cos φ of experimental model as function of current of DC side in the rectifier regime. We can see that if the current of load is within the range 4-12 A then cos φ is growing and when the value of current reached 12 A then cos φ is stable approximately 0.90. Also we can see that cos φ is very similar when smoothing inductance L without L is used. The inductance of the used coil was 0.848 mH.

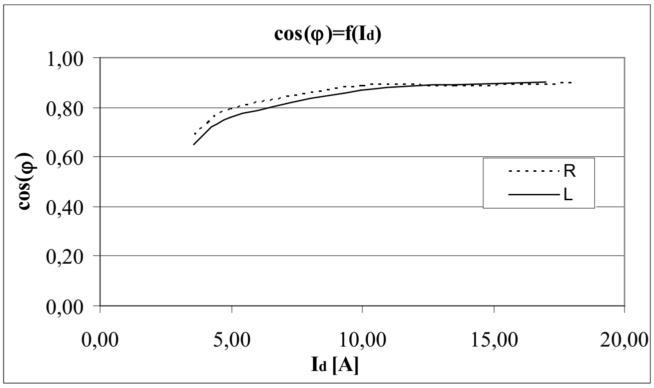

Fig. 20. Dependence of cos(φ) of I_d in rectifier regime.

Fig. 21 presents the characteristic of cos φ of experimental bidirectional power flow regulator model in the recuperation regime. There we can see negative current of DC side what confirms that electrical energy is recuperated to AC network. Also we can see that better cos φ = 0.28 has been reached during the experiments that is not enough; therefore another experiment is necessary to transmit higher power from DC to

AC side and it will be done using more powerful DC source than in this experiment.

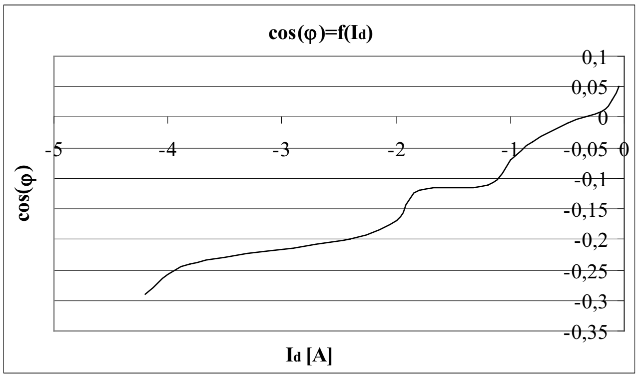

Fig. 21. Dependence of cos(φ) of I_d in recuperation regime.

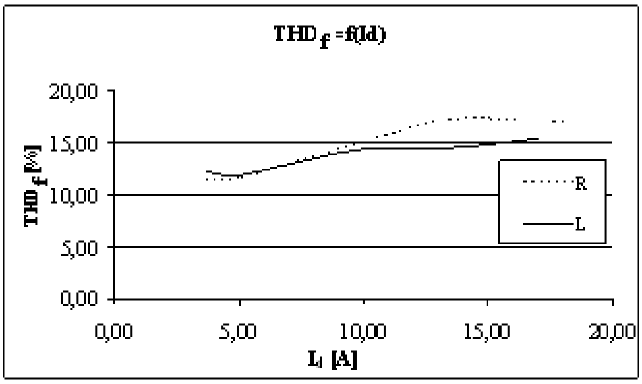

Fig. 22. Dependence of THD_f of $I_d$in rectifier regime.

$$THD_f = 100 \cdot \sqrt{\frac{\sum_{n=2}^{n=\infty} I_{(n)}^2}{I_{(1)}^2}} = 17.03\% . \quad (4)$$

In Fig. 22 we can see total harmonic [3] distortion (Fund) of current of AC network as a function of DC current of DC grid. The characteristic shows that THD_f has a growing character from 12 % up to 18% what is acceptable percentage for that kind of experimental model. There is formula (4) which describes total harmonic distortion (Fund) in rectifier regime and formula (5) which describes in the recuperative regime. Fig. 22 shows THD_f of two experimental variants when smoothing filter L was used and when only rheostat as a load was used. Both characteristics are very similar to each other. It means that there is not big influence of reactance of L to THD_f.

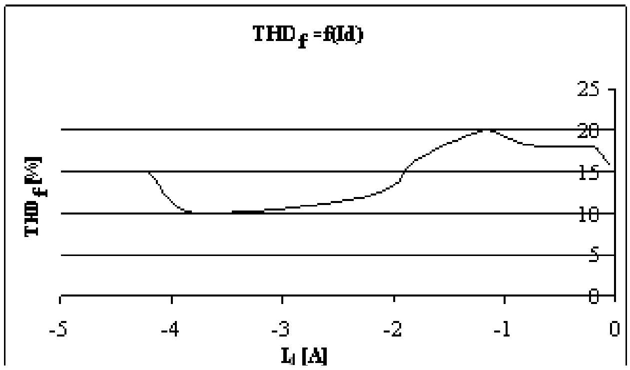

Fig. 23. Dependence of THD_f of I_d in recuperation regime.

$$THD_f = 100 \cdot \sqrt{\frac{\sum_{n=2}^{n=\infty} I_{(n)}^2}{I_{(1)}^2}} = 14.89\% . \quad (5)$$

Fig. 23, shows characteristic of THDf as a function of DC current of the inverter regime. As we see THD_f is within 10 – 20 percents.

IX. CONCLUSIONS

Elaborated experimental bidirectional power flow regulator confirmed a hypothesis that this kind of new solution can be used for recuperation of electrical energy of tramcars and trolleybuses in power substations of electrical transport. Elaboration of that kind regulator can save electrical energy in electrical transport of Riga.

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