UPGRADE OF THYRISTOR RECTIFIERS IN A THERMAL POWER PLANT "NIKOLA TESLA A"

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Abstract: In the paper the upgrade procedure for high-power thyristor rectifiers in the thermal power plant "Nikola Tesla A" is described. Originally, thyristor rectifiers were not designed for operation without batteries. Thus it may happen that, in a critical situation, battery failure would induce the thyristor rectifier switch off, leaving all the consumers without a direct voltage. In such a situation, it is very important for rectifier to stay in operation, continuing power supply of the critical consumers with a stable direct current, even if the extremely heavy electrical disturbance occurs in a local direct current grid.

Improvements of the thyristor rectifiers based on the digital controller of type "DRI 07" were described in detail. Responses of the rectifier digital regulators were presented in the cases of the battery disconnection and connection, in circumstances of permanent operation in the voltage regulation mode, as well as during the alternation of the voltage and current regulators in a trickle charge mode. The effect of the adaptive PI regulator on dynamic characteristics of rectifier was analyzed during the abrupt load current variations. Applied procedure for the battery availability detection was described, as well as its influence on the characteristics of the storage battery.

Key words: *thyristor rectifier, adaptive regulator, digital control, robustness, electrolytic capacitor*

УНАПРЕЂЕЊЕ ТИРИСТОРСКИХ ИСПРАВЉАЧА У ТЕРМОЕЛЕКТРАНИ "НИКОЛА ТЕСЛА А"

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Кратак садржај: У раду је описан поступак за побољшавање карактеристика тиристорских исправљача велике снаге у термоелектрани "Никола Тесла А". Тиристорски исправљачи примарно нису били предвиђени за рад без батерије. Тако може да се деси да, у критичној ситуацији, због испада батерије дође и до испада тиристорског исправљача и останка свих потрошача без једносмерног напона.

Детаљно су описана унапређења тиристорских исправљача са дигиталним регулаторима типа "ДРИ 07". Приказани су одзиви дигиталних регулатора исправљача у случајевима искључења и укључења батерије, и то у варијантама непрекидног рада у режиму регулације напона исправљача, као и приликом смењивања регулатора напона и струје исправљача у режиму допуњавања. Анализиран је утицај адаптивног ПИ регулатора на динамичке карактеристике исправљача приликом наглих промена оптерећења. Описан је примењени поступак провере присуства батерије и његов утицај на карактеристике акумулаторске батерије.

Кључне речи: *тиристорски исправљач, адаптивни регулатор, дигитално управљање, робусност, електролитски кондензатор*

1. INTRODUCTION

In power plants and big industrial facilities usually the high-power thyristor rectifiers and lead-acid storage batteries represent the bases for the uninterruptible direct current power supply system [1, 2]. Generally, the most important part of the uninterruptible power supply system is a storage battery, having a task to provide the several hours lasting power supply autonomy for the critical consumers if the mains alternate current power supply fail in a power plant [3, 4]. Consequently, in the most of older power plants were used simpler battery chargers, *i.e.*, thyristor rectifiers without output filter capacitors. Such simple configuration has certain advantages, primarily manifested in significantly eased maintenance. In this case in the thyristor rectifier power circuit there are not electrolytic filter capacitors, nor the auxiliary power equipment. Thus the user's manipulation is substantially simplified during the yearly battery cycling process. Also, evasion of the use of electrolytic filter capacitors may be very important during the rectifier operation in thermal power plants, where the ambient temperature, due to the air-conditioning failure or even its lack, may easily surpass permitted 40-45°C [5]. Moreover, during the thyristor rectifier operation without filter capacitors, battery failure may be detected immediately, but this is not possible in the case of operation with output electrolytic capacitors. Battery connected to the output contacts of the thyristor rectifier behaves like an extremely high capacitor and almost the current well, enabling the easy filtration of electromagnetic interference and overvoltages in facility on the regular rectifier operation and the consumer power supply with a steady direct current.

On the other hand, one must not expect a battery to be absolutely reliable and in all circumstances stable source of direct current. Both temporary or permanent battery faults may be affected by a number of causes, starting with battery fuse reaction, then increase of the intermediate resistance of the battery cell connections, and, finally, mechanical damage and breach of the battery circuit. Thus it may happen that, in a critical situation, battery fault would induce the thyristor rectifier switch off, leaving all the consumers without a direct voltage, including even the protective devices. In such a situation, it is very important for rectifier to stay in operation, continuing power supply of the critical consumers with a stable direct current.

In the paper is presented the upgrade procedure of the existing thyristor rectifiers in the power plant, delivered in a simple power circuit configuration without output capacitors, improved on a variant with output LC filter and digital regulators of increased robustness.

2. CHARACTERISTICS OF THYRISTOR RECTIFIERS DRI 220-250 AND DRI 110-500 BEFORE RECONSTRUCTION

Digitally controlled rectifier DRI 220-250 is one of the "DRI" type thyristor rectifiers, developed and manufactured in Institute of Electrical Engineering "Nikola Tesla" [6]. Device control is performed by the rectifier digital controller of type "DRI 07", based on microcontroller "Intel" 80C196KB16. The control functions of the microprocessor card "uP3" were realized by "C" language software, with the principal tasks of impulse generation of thyristor drivers and realization of the voltage and current regulators [6]. Thyristor rectifiers of "DRI" type have functions of a triple automatic switch in the case of permanent rectifier failure, "soft start", availability detection and the phase sequence of the alternate mains voltage, detection of the high and low battery voltage, overload, the bridge rectifier imbalance caused by the thyristor failure, as well as the failure signaling using the relay contacts and LED diodes [7]. Rectifier voltage and current regulation loops are realized by software.

Rectifier digital controller of type "DRI 07" is mounted in a closed aluminum box, with a lateral connector on both left and right sides. In the front side of the box are mounted fuses for both alternate and direct current circuits of the control electronics, as well as potentiometer for the voltage adjustment, serial communication cable connector and the microprocessor reset taster. Power supply of the controller "DRI 07" was accomplished through the DC/DC converter, having a bilateral power supply, both from the mains voltage (220 V, 50 Hz) and the storage battery voltage [7].

On the occasions of the rectifier operation with vented lead-acid batteries, a four-state switch enables both manual selection of the battery charging mode (trickle, boost and equalizing charge), as well as the automatic battery charging mode according to the IUU characteristic [6, 7]. In configuration of the thyristor driver are six electrically isolated channels for the thyristor gate impulses. The measured value of the output voltage is brought on the microcontroller's A/D converter across the voltage divider and filter stage. In the same device is also included circuit for detection of the battery disconnect. The appearance of the high voltage ripple, *i.e.*, A high alternate component of the output voltage, represents a signal of the battery unavailability. Of course, this is the case when there are not filter capacitors in the rectifier output. Signals from shunts of rectifier and battery circuits are transferred to differential comparators, followed by their further transfer of adjusted and filtered values towards the microcontroller. Also, voltage and current signals are being transferred to the conditioners, having the output current range of 4 - 20 mA. Beside the processing in microcontroller, current signal is also being transferred to the 100 Hz active filter, used for detection of the rectifier bridge imbalance in the cases of the thyristor failure or the ultrarapid fuse blow. Overload protection is realized as an independent analog circuit, blocking the driver impulses transfer toward the gates of thyristors if its reaction occur. Separate part of the analog electronics printed circuit board is the earth fault relay, having detection capability of the conductive path between the positive or the negative pole of the connected storage battery, from one side, and the grounding system, from the other. Threshold resistance for the earth fault relay reaction may be set in the range between 10 kΩ and 1 MΩ [6].

Electrical isolation was seriously treated during the development of the "DRI 07" digital controller, since the phase controlled rectifiers in the uninterruptible power supply systems are usually designed for the direct current power supply for consumers not electrically connected to the grounding system. Since the "DRI 07" control electronics has both power supplies of alternate mains voltage (3·380 V, 50 Hz) and battery direct voltage, it is very important not to connect different voltage potentials that would affect the correctness of measurement, control or communication electronics, and particularly the user's safety. Therefore all the alternate voltages are mutually separated by using the print transformers, thyristor gates by the impulse transformers, and all the logical inputs of the control electronics are isolated by the optocouplers. Serial communication channel, of the standard RS 485, is also optically isolated using the integrated circuit MAX 1480A, with a maximum baud rate of 2.5 Mb/s [7].

3. DESCRIPTION OF RECTIFIERS IN THE THERMAL POWER PLANT "NIKOLA TESLA A" AND TECHNICAL DEMANDS FOR RECONSTRUCTION

In 2003. Institute of Electrical Engineering "Nikola Tesla" delivered to the thermal power plant "Nikola Tesla A" six rectifiers with analog control electronics (three ARI 220-250, two ARI 110-500 and one ARI 24-70), designed for the uninterruptible power supply system and telecommunication equipment on power blocks A1, A2 and A3. Following years, between 2007. and 2010, another nine thyristor rectifiers, this time with a digital controller, were delivered to power plant (five DRI 220-250 and four DRI 110-500).

All the fifteen manufactured rectifiers were delivered without output filter capacitors, since originally thyristor rectifiers were not designed for operation without batteries. Nevertheless, battery is not an absolutely reliable source of direct current. Thus, in a critical situation of battery failure it would be very important for rectifier to stay in operation, continuing power supply of the critical consumers with a stable direct current, even if the extremely heavy electrical disturbance occurs in a local direct current grid. Therefore, in the year 2011. users requested an upgrade of the existing rectifiers in order to increase the robustness of the uninterruptible direct current power supply system in the power plant. Additional request was that electric transient must not affect any protective function that turns the rectifier off, if the variation of the consumer's current occur in a range from 1% up to 100% of the nominal load, regardless of the possible simultaneous disconnection or connection of the storage battery. Moreover, alternative procedure was requested for a relatively quick detection of the battery availability on the rectifier's output contacts.

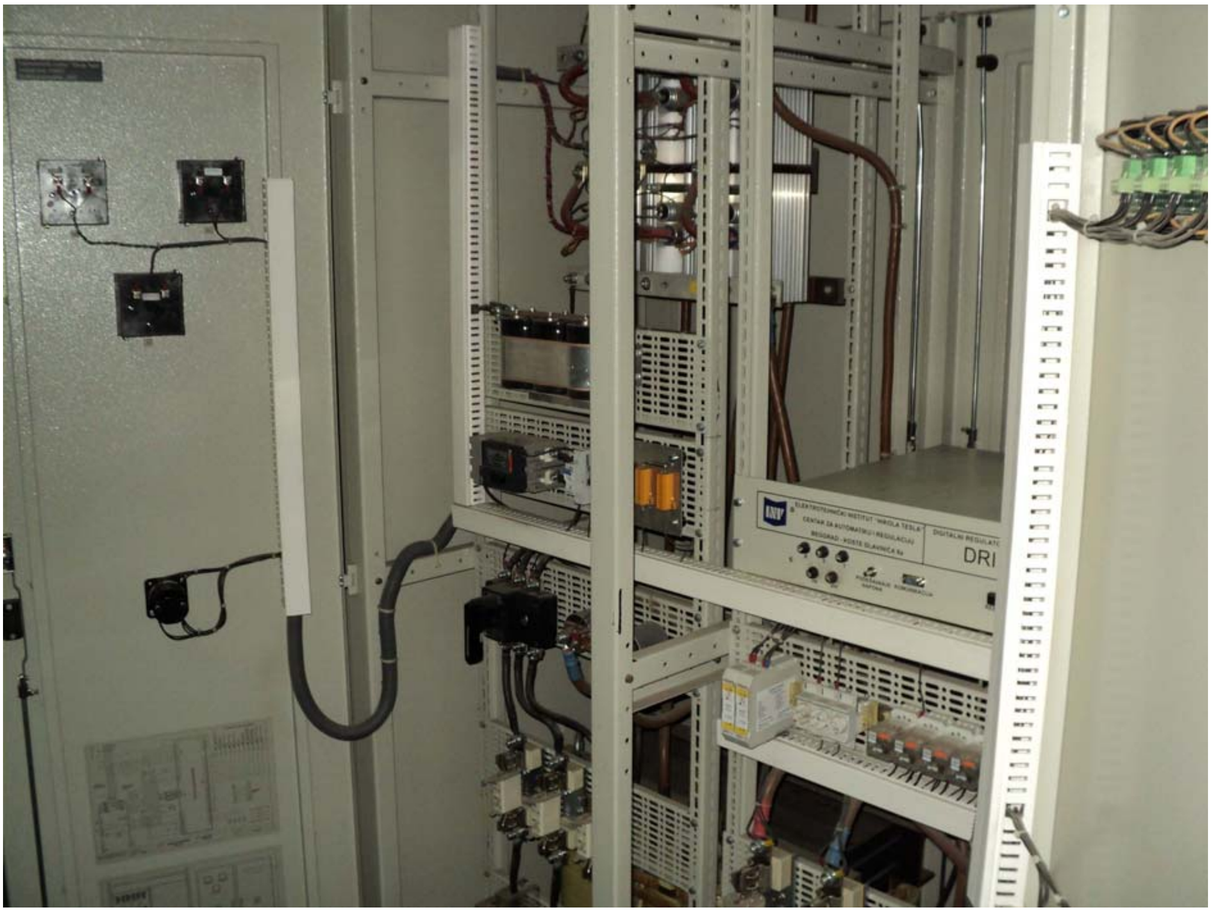

Figure 1. The internal appearance of upgraded rectifier DRI 220-250 in the power plant "Nikola Tesla A"

Such a rigorous request regarding the rectifier's dynamic characteristics could be only met by the simultaneous reconstruction of the thyristor rectifier power circuit and modification of the electronic control circuit. Reconstruction of all the fourteen rectifiers in the power plant, with nominal output voltages of 110 V and 220 V, was performed. Of the mentioned number, nine upgraded rectifiers were of type "DRI 07", with digital controllers, alongside with five older devices with analog control electronics. In order to fulfill all the specified request, on all the high-power rectifiers were mounted output filter electrolytic capacitors, altogether with the auxiliary power circuit components (protective switch, capacitor discharging resistors, fuses). Beside the modification of the power circuit, also upgrade of the voltage and current digital regulators was necessary, as well as the addition of the EMI filters and improvement of several protective and signaling functions.

Digital current regulators were realized as ordinary PI regulators, while the digital voltage regulators were realized as linear adaptive PI regulators. In the case of voltage regulators was implemented gain scheduling with adaptive, current related linear variation. According to the immediate value of the output current, coefficient of proportional gain (K_p) varies from very high value in idle operation, decreasing to the steady state value of K_p, for higher rectifier currents. Adaptive action has the greatest effect on the rectifier's operation during the abrupt variations of current from several amperes up to 50 - 100 A. Both activation of adaptive action, as well as values of initial coefficient K_{p0}, steady K_p and its current threshold may be set using the serial communication of standard RS 485. Therefore, this procedure enables performance of extensive tests on rectifiers in their real operating environment.

Installation of additional EMI filters proved invaluable in the harsh environment of thermal power plant. Rectifier digital control electronics was not much vulnerable during the previous years, when rectifiers always operated with batteries. Yet, when large filter capacitors were added to rectifiers, far exceeding 10000 μF, commutation overvoltages or disturbances affected by the high-power equipment in the direct current distribution system led to the appearance of numerous malfunctions of control electronics, particularly during the rectifier's operation with negligible load current. Extensive use of EMI filters enabled reliable rectifier operation in all battery charge modes.

Since the output capacitors were mounted, the user needed new procedure for detection of the battery availability, since the old method relying on detection of high alternate output voltage became additional one, preventing damage on the direct current consumers in the case that both battery and output capacitors fail. Therefore, the modified battery availability test was resumed from the DRI-PT series of thyristor rectifiers made in Institute of Electrical Engineering "Nikola Tesla" [8, 9]. Battery availability test is performed in the following way: after every 30 minutes of operation, the rectifier output voltage of rectifier DRI 220-250 is being decreased down to 215 V (1.95 V/cell in a battery comprised of 110 cells) [8]. As long as the battery availability test lasts, a battery is discharged if it is correct. If a breach occurred in a battery circuit, a consumer voltage is still kept on acceptable value, inside the boundaries of ±10% variations of the nominal voltage. Brief battery discharge every 30 minutes enables timely detection of the potential battery failure.

4. EXAMINATION RESULTS OF RECTIFIER DYNAMIC CHARACTERISTICS AND DISCUSSION

During the examinations of thyristor rectifier DRI 220-250 (nominal trickle charge voltage 245.3 V, software current limit 230 A) in thermal power plant, responses of the voltage and current regulators were recorded. Acquisition of the voltage and current waveforms was performed using the 100 MHz digital oscilloscope "Fluke" 196C. Current signal was measured using the current clamp "Chauvin Arnoux" PAC22 (1400 A, 0-10 kHz), while the voltage signal was procured using the oscilloscope voltage probe "Metrix" HX0005 (450 MHz, 10:1, 14 pF).

In Fig. 1 is presented internal appearance of the upgraded rectifier DRI 220-250, with output filter capacitors and improved "DRI 07B" control electronics. Schematic power circuit diagram of upgraded thyristor rectifier is presented in Fig. 2. During the reconstruction, alongside the other less noticeable circuits, two perforated boards were added, one with electrolytic capacitors (upper board in a left front field of the cabinet, Fig. 1) and the other with high-direct-current switch, resistors and fuse (board bellow the capacitors in a left front field, Fig. 1). Use of the spacious cabinet and perforated boards enabled easy addition of the new equipment.

After completion of the upgrade procedure, all rectifiers in the thermal power plant "Nikola Tesla A" were tested on occurrence of the battery disconnection and later connection during the rectifier's operation with consumers. Real industrial consumers were simulated by high-power resistors, capable to operate with direct currents of several hundred amperes. Battery and some of resistive consumers were disconnected from the rectifier by the high-current switch in a direct current distribution board. A few seconds later, the battery would be in the same way connected to rectifier. All mentioned manipulations must not lead to switch off or failure of the tested rectifier.

Thyristor rectifiers DRI 220-250 and DRI 110-500 could not have identical responses to abrupt changes of load type and its current. For instance, if the rectifier DRI 220-250 operated with software current limit of 230 A in a trickle charge mode, it could easily enter a current regulation mode with two resistors of 3 Ω and partially discharged battery. On the other hand, reaching the current limit would be much more difficult with device DRI 110-500, an 500-ampere rectifier. Therefore, procured waveforms also may be significantly different.

In the Fig. 3 were presented voltage and current waveforms of rectifier DRI 220-250 recorded during the disconnection of battery, while in Fig. 4 were presented waveforms recorded during the later reconnection of the same battery. The batteries had vented lead-acid cells, with a nominal capacity of 800 Ah.

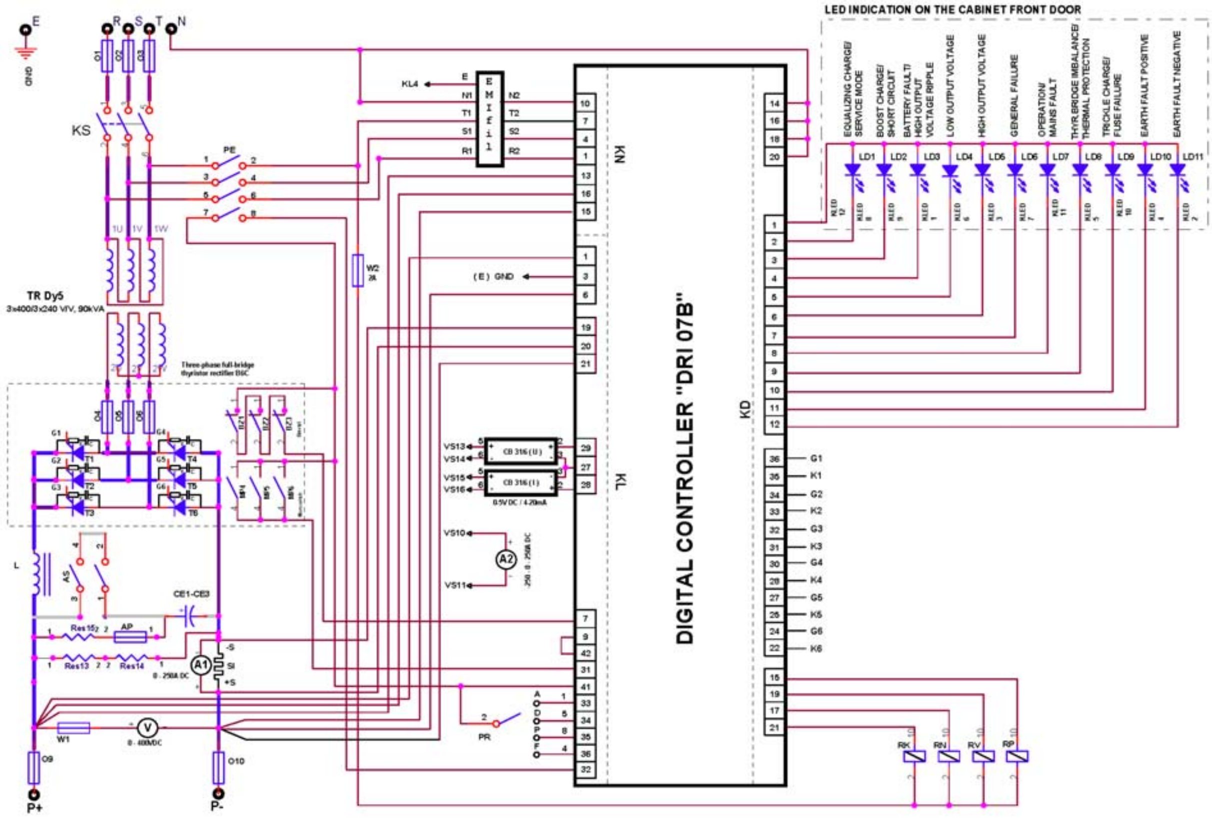

Figure 2. Schematic power circuit diagram of upgraded thyristor rectifier DRI 220-250

Waveforms presented in Figs. 3 and 4 are complex ones, since there are no responses of individual PI regulators, but the transition from the current PI regulator to adaptive voltage PI regulator (Fig. 3), followed by another transition from voltage to the current regulator (Fig. 4). Transient in the Fig. 3 lasts nearly 60 ms, with an integral time constant of the regulator being T_i = 17.8 ms. Current declines from 230 A down to 110 A, also losing its significant component since the rectifier DRI 220-250 remains in operation only with resistive load. Since the battery has great equivalent capacitance, alternate current component through a battery (for a full load) may reach up to 30% of the nominal rectifier current.

In Fig. 4 is presented transition from the voltage regulation to the current regulation mode, affected by connection of the battery and another resistor to the rectifier DRI 220-250 operating only with pure resistive consumer. The digital current PI regulator may be activated in two ways: by reaching the threshold of the instantaneous value of current necessary to activate the current regulator (in this case, 1.66 times of current limit in a trickle charge mode, that is 380 A) or by exceeding the average value of the current limit, but with a time delay of nearly 200 ms. From Fig. 4 may be seen that the first condition for the activation of the current PI regulator was fulfilled, reaching the threshold of 380 A after nearly 35 ms, leading to regulators alternation and the creation of the transient process lasting about 70 ms. Mentioned thresholds for instantaneous and average value of the output current eliminate negative effects of noise or commutation overvoltages, preventing the successive alternations of voltage and current regulators.

In Fig. 5 are presented voltage and current waveforms recorded during the disconnection of the battery and one resistive consumer from rectifier DRI 110-500, while in Fig. 6 are presented adequate waveforms after following the reconnection of congenial 110 V battery. Opposite to the data presented in Figs. 3 and 4, transients in Figs. 5 and 6 were consequence of only the adaptive PI voltage regulator operation. In the case of 500-ampere rectifier, available resistors and battery could not enable reaching of the rectifier current limit in a trickle charge mode. Therefore, transient processes were much smoother and shorter, since continually just one digital regulator has been active.

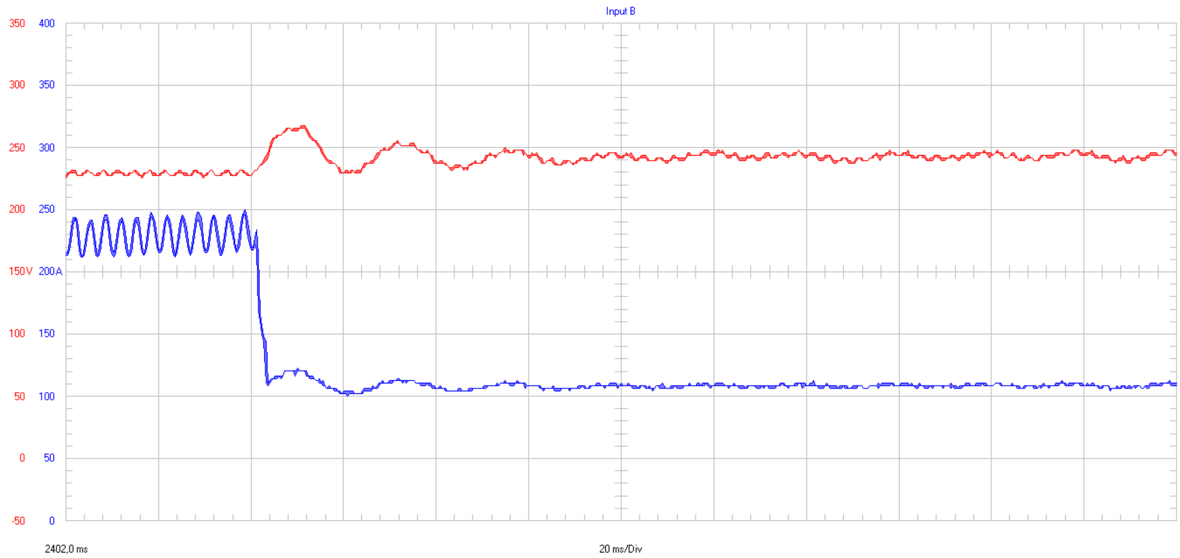

Figure 3. Voltage (up, red) and current (down, blue) waveforms recorded during the disconnection of the battery and one resistive consumer from rectifier DRI 220-250

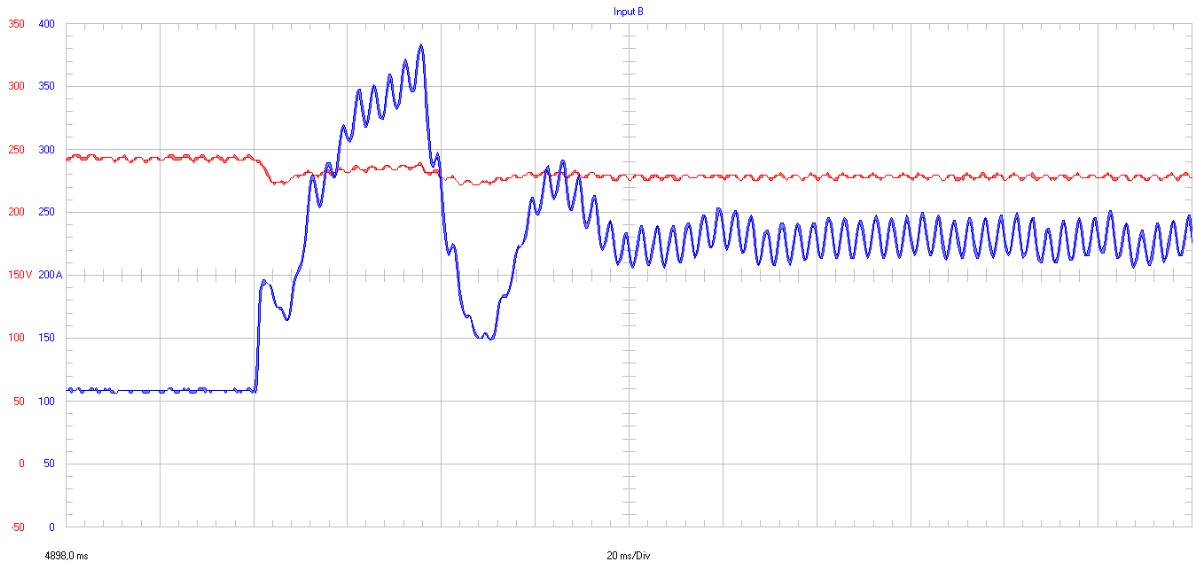

Figure 4. Voltage (up, red) and current (down, blue) waveforms recorded during the connection of the battery and one resistive consumer to rectifier DRI 220-250

As it was earlier mentioned, reconstruction also comprehended older thyristor rectifiers of the “ARI” type, with analog control electronics. These devices utilized common analog PI regulators, with operational amplifiers of type “LM741”, having parameters K_p = 0.45 and T_i = 33 ms. Since the analog regulators have, let say, “indefinitely high sampling frequency”, they usually have faster response than ordinary digital PI regulator. Yet, depending on the type of controlled process, as well as the regulator parameters, even simple digital regulators may be concurrent to their analog counterparts. Nevertheless, if the more complex regulation structures have to be implemented, the advantages of digital regulators emerge. Therefore, in order to compare the responses of upgraded digital regulators with older analog devices, also the current and voltage waveforms of rectifier ARI 220-250 were also presented.

In Fig. 7 are presented current and voltage waveforms of thyristor rectifier with analog control electronics ARI 220-250 in a moment of the disconnection of battery. In Fig. 8 are presented corresponding waveforms during the battery reconnection to upgraded rectifier ARI 220-250, with output filter capacitors. As may be seen after comparison of analogous waveforms (Fig. 3 and Fig. 7), in the case of alternation of current and voltage regulators, affected by the disconnection of battery, digital devices have a great advantage, with much shorter transient (about 60 ms, in comparison with nearly 220 ms), as well as much lower overshoot (9%, in comparison with 18%). Digital regulators demonstrated advantage also during the later battery reconnection. While the digital current regulator of device DRI 220-250 activated after a time delay of 35 ms, necessary for current to rise up to 380 A, analog current regulator of rectifier activated after a time delay of 120 ms. Afterwards, transient processes had a similar duration of nearly 60 ms. By the way, the digital current regulator also has a time delay if the triggering condition is not immediate, but rather average current value. If the current in Fig. 4 did not reach a value of 1.66 times of the current limit, current regulator would activate after the time delay of nearly 200 ms. Nevertheless, digital regulator in DRI 220-250 has the capability to activate by the high immediate current, opposite to the analog regulator in ARI 220-250.

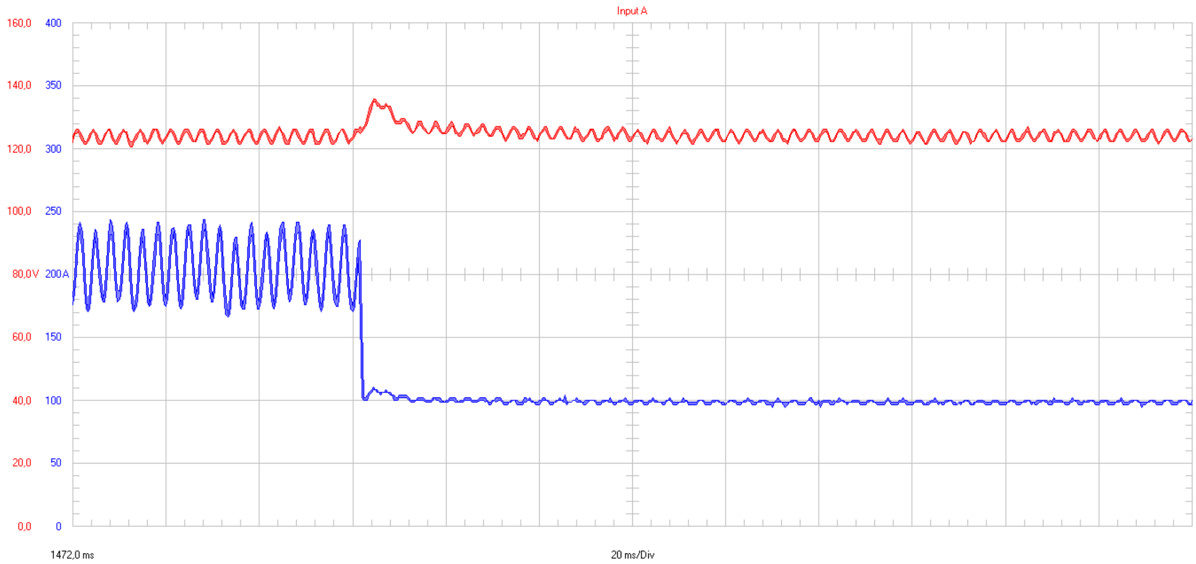

Figure 5. Voltage (up, red) and current (down, blue) waveforms recorded during the disconnection of the battery and one resistive consumer from rectifier DRI 110-500

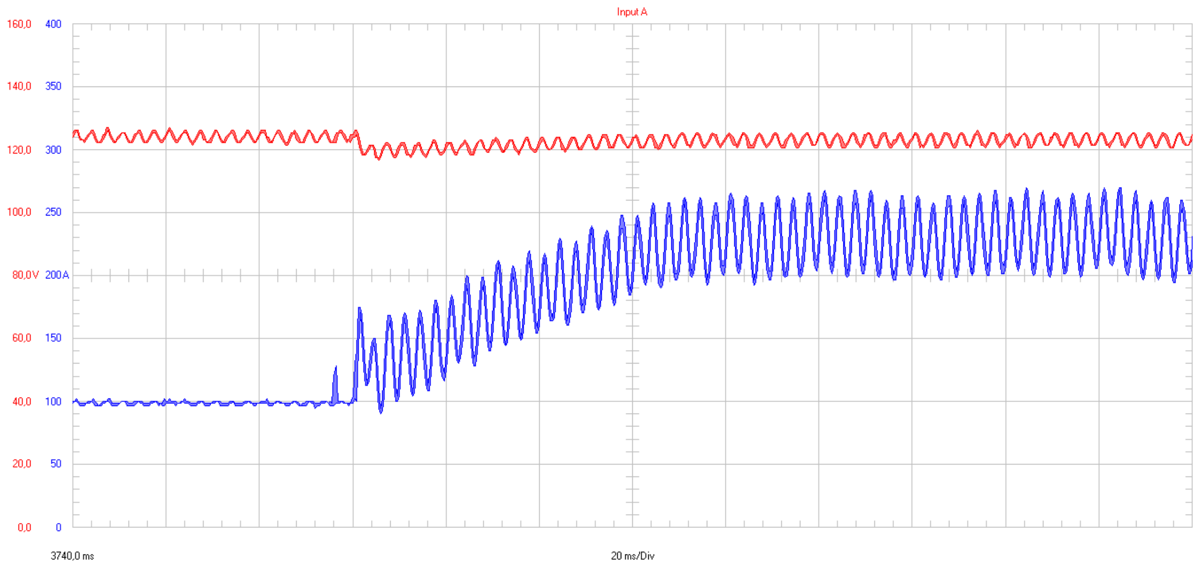

Figure 6. Voltage (up, red) and current (down, blue) waveforms recorded during the connection of the battery and one resistive consumer to rectifier DRI 110-500

During the examination of upgraded rectifiers were also analyzed current and voltage waveforms of 500-ampere rectifiers ARI 110-500, constantly operating in a voltage regulation mode during the manipulations with battery and resistors. As may be expected, the analog PI voltage regulator had better responses than its digital counterpart on DRI 110-500. Yet, current and voltage waveforms on ARI 110-500 were similar to waveforms recorded on the rectifier with digital regulator. Therefore, these waveforms were omitted as recorded differences were not significant.

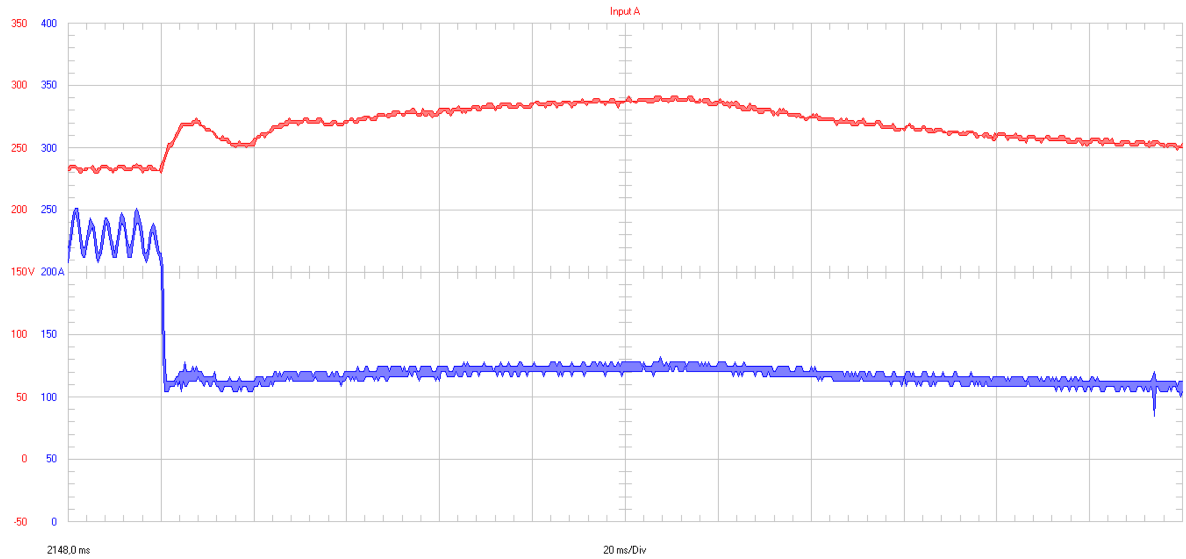

Figure 7. Voltage (up, red) and current (down, blue) waveforms recorded during the disconnection of the battery and one resistive consumer from rectifier ARI 220-250

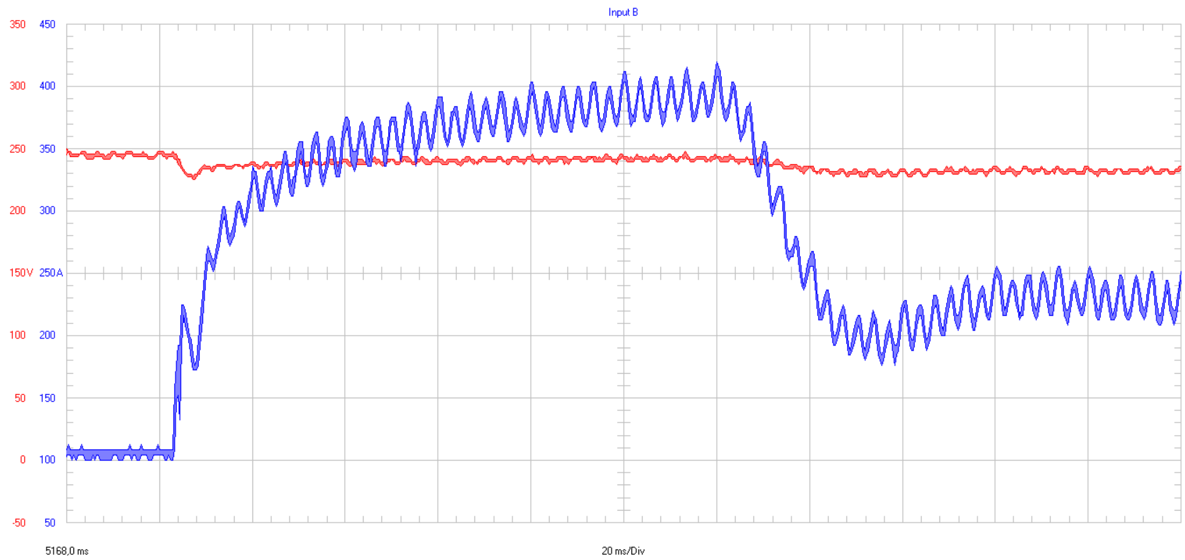

Figure 8. Voltage (up, red) and current (down, blue) waveforms recorded during the connection of the battery and one resistive consumer to rectifier ARI 220-250

5. CONCLUSION

In the paper were presented upgrade procedures and examination results for high-power rectifiers in the thermal power plant “Nikola Tesla A”. In order to increase robustness of the uninterruptible direct current power supply system, reconstruction of all the installed rectifiers in a power plant was performed. Upgrade procedure was comprised of two major undertakings: reconstruction of the rectifier power circuits and improvement of control electronics.

As a part of power circuit reconstruction, filter electrolytic capacitors and auxiliary protective equipment were mounted in order to enable rectifier to be the stable and robust source of direct current even in the case of battery failure. Improvement of the control electronics was mainly focused on the creation of new software, particularly in the application of new regulation procedures and modification of existing protective functions and signalization. Directly programmable linear adaptive PI regulators and improved conditions for regulators alternation were implemented in the control software. A new procedure for detection of the battery availability was also applied.

Several characteristic current and voltage waveforms recorded during the manipulations with the battery and resistive load were presented. Both the waveforms on upgraded rectifiers with digital ("DRI" type), as well as an analog controller (older "ARI type") were analyzed. Advantages and drawbacks of improved digital regulators over their older analog counterparts were specified.

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