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UGRADNJA AUTOTRANSFORMATORA 400/220 KV U TS KONJSKO

INSTALLATION OF AUTOTRANSFORMER 400/220 KV IN SUBSTATION KONJSKO

Marko Mičanović[1], Krešimir Meštrović[2]

[1]RAVEL d.o.o., Prilaz Vladislava Brajkovića 13 , Zagreb
[2]Zagreb University of Applied Sciences, Electrical Engineering Dept., Konavoska 2, Zagreb

SAŽETAK

Projektiranje visokonaponskih elektroenergetskih objekata kompleksan je postupak koji iziskuje angažman velikog broja ljudi različitih struka. U ovom radu opisali smo kako smo projektirali ugradnju autotransformatora 400/220 kV i njegov spoj na elektroenergetsku mrežu preko 220 kV i 400 kV sabirnica u TS Konjsko. Kako su transformatorske stanice od presudne važnosti za pravilno i sigurno funkcioniranje elektroenergetskog sustava, vrlo je važno posebnu pozornosti pridati njihovom pravilnom dimenzioniranju. U svrhu osiguranja ljudi i opreme od nepoželjnih pojava kao što su uništenje opreme ili ugrožavanje ljudskog života, neophodno je dokazati kako je novo projektirani dio postrojenja projektiran i usklađen s normama i pravilnicima koje opisuju ispavan način projektiranja pojedinih cjelina visokonaponskog postrojenja.

Ključne riječi: *cijevne sabirnice, spojni vod, primarna oprema, uzemljenje, instalacija zaštite od munje, sile na vodiče*

ABSTRACT

The design of high-voltage power facilities is a complex procedure that requires the involvement of a large number of people from different professions. This paper describes the issue of installing a 400/220 kV autotransformer and its connection to the power grid via 220 kV and 400 kV busbars in TS Konjsko, related to the design of primary circuits in high-voltage power facilities. Since transformer stations are of crucial importance for the proper and safe functioning of the power system, it is very important to pay special attention to their proper dimensioning. In order to protect people and equipment from undesirable phenomena such as the destruction of equipment or the endangerment of human life, it is necessary to prove that the newly designed part of the plant is designed and harmonized with the norms and regulations that describe the proper way of designing individual parts of the high-voltage plant.

Keywords: *busbars, connecting line, primary equipment, grounding, lightning protection installation, forces on conductors*

1. UVOD
1. INTRODUCTION

Due to the increasing construction and connecting to the renewable sources in the power grid of Dalmatia, the need occurred to increase the capacity of 400/220 kV transformation within TS KONJSKO which is to be carried out by installing a new autotransformer – AT3 and connecting it to the 220 kV and 400 kV plants. The necessity of this project has been a recognised problem for a longer while which is evidenced in the fact that it was foreseen in the Croatian Transmission System Operator's ten-year power grid development plan 2021 to 2030. [1] In order for the installation of the new autotransformer and its connection to the existing grid through the newly equipped 220 kV and 400 kV transformer bays to be carried out in a safe and reliable way, the following items have to be executed:

- Install a 400/220 kV autotransformer in the planned location
- Extend the 400 kV busbars for the width of a transformer bay
- Equip the new 400 kV transformer bay
- Equip the new 220 kV transformer bay
- Execute the 220 kV cable connection
- Perform the correct grounding and lightning protection installation

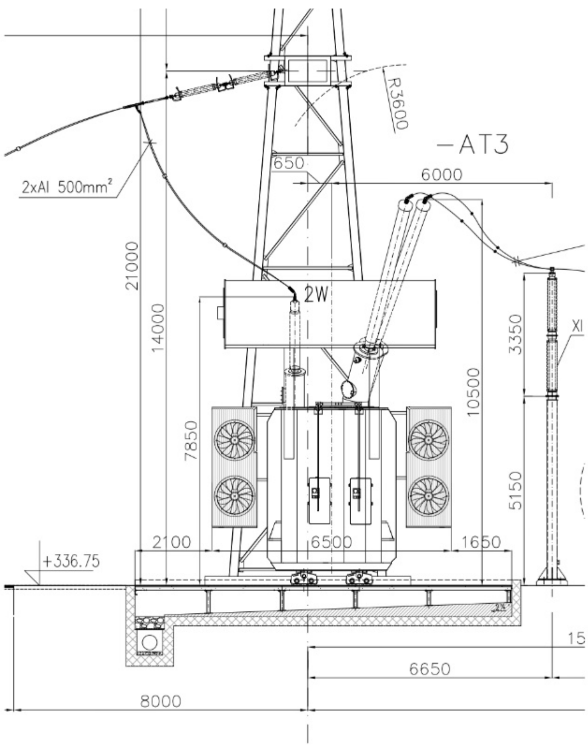
Due to the disposition of the plant and the chosen location of the new 400 kV and 220 kV transformer bays as well as the -AT3 autotransformer, the typical construction with the completely airborne connection with overhead lines between the autotransformer and the 220 kV and 400 kV busbars was not possible in this case, but a 220 kV cable connection between the two 220 kV segments of the new 220 kV transformer bay had to be carried out.

2. UGRADNJA AUTOTRANSFORMATORA 400/220 KV

2. INSTALLATION OF AUTOTRANSFORMER 400/220 KV

Since the project calls for the new autotransformer -AT3 to work parallelly with two existing autotransformers -AT1 and -AT2, the prerequisites for the parallel operation of these transformers have to be met. The first prerequisite of the parallel work of transformers refers to the equal phase shifts between the primary and the secondary windings, and since the new autotransformer is of the identical connection group and clock number as the existing transformers (YNa0+d5), this prerequisite has been met [2]. The second prerequisite of parallel work of transformers refers to the ratio of the number of turns on the primary winding and on the secondary winding, and since the new autotransformer has same turn ratio as the existing transformers (400/231 kV), this prerequisite has been met [2]. The third prerequisite for the parallel work of transformers refers to the difference in the short-circuit voltage of individual transformers which mustn't be greater than 10%. The short circuit voltage of the new autotransformer -AT3 is u_k=12% [3], while the short-circuit voltage of the existing autotransformers -AT1 and -AT2 is equal to $u_{k(AT1)}$=11,67% and $u_{k(AT2)}$=11,73% [2]. It can be deduced from all of the above that the prerequisite referring to the short-circuit voltage for parallelly connected transformers has been met. The fourth prerequisite for the parallel operation of transformers refers to the ratio of the nominal power of transformers that mustn't exceed 1:2, and since the new autotransformer is of the identical nominal power as the existing transformers (400 MVA), this prerequisite is met [2].

For the purpose of connecting the autotransformer -AT3 to the 400 kV and the 220 kV busbars, the autotransformer has to be mounted onto the newly constructed oil containment sump. In case of a transformer breakdown, there is a possibility of the transformer oil leakage into the environment. Such leakage has to be disposed in an environmentally safe and acceptable way. The dimensions of the oil containment sump are to be determined in line with the HRN EN 61936-1:2021 [4] standard, taking into account the width, length and height of the transformer to the top edge of the transformer conservator, as well as the oil quantity contained in the transformer.



***Slika 1** Presjek novo ugrađenog autotransformatora -AT3 [5]*

***Figure 1** Section of the newly installed autotransformer -AT3 [5]*

The new autotransformer -AT3 is to be mounted with a small offset, but practically in the centreline of the existing autotransformers -AT1 and -AT2. The size of the offset from the centreline of the existing autotransformers is 650 mm, and the reason for it is achieving the appropriate voltage clearances. Actually, due to the transformer's bushings height at the 400 kV side and the height of the existing portal crossarm that has been continued for the newly designed transformer bay, the transformer must be offset from the centreline of the portal (i.e., the centreline of the existing autotransformers -AT1 and -AT2) so as to achieve the appropriate voltage clearance between the 400 kV transformer bushing and the portal crossarm in the amount of 3,600 mm.

3. DOGRADNJA 400 KV SABIRNIČKOG SUSTAVA

3. EXTENSION OF 400 KV BUSBAR SYSTEM

The existing 400 kV double busbar system is designed with tubes in E- AlMgSi0,5F22 alloy, has the dimension of 220x8 mm, and nominal current of 5,862 A [2]. The nominal current of the 400 kV busbars has been defined with regard to the maximum possible load at the value of 3,000 A. For its superior properties, the abovementioned aluminium alloy is most often used for tubular connections in high-voltage plants. Along with good conductivity and mechanical strength and low weight, tubes made out of the E-AlMgSi0,5F22 alloy are well machinable, weldable, are corrosion resistant and are shipped in lengths that are favourable with regard to the plant disposition. The new part of the 400 kV busbars will be made from E- AlMgSi0,5F22 tubes of the identical dimensions as the existing tubes of the 400 kV busbars.

In order to prove that it is possible to use a certain type of conductor for a certain purpose, certain checks have to be made. The selected conductors have to be able to withstand all the working conditions for a normal exploitation, but also all the working conditions in case of a short circuit. When designing the busbar system with the tubular busbars attention has to be paid to the busbars' strain due to small velocity wind, maximum busbars' strain, maximum busbars sagging and maximum load to the supporting insulators.

The small velocity wind is an issue for tubular connections due to the natural frequency of the tubular busbars which can result in oscillating amplitudes significantly higher than permitted. In this case, antivibration cable of a certain diameter and length has to be inserted into the tubular conductors which will result in damping of the oscillation. By inserting the antivibration cable into the tubular busbars, the oscillating amplitude of the busbars is limited to 10 mm. This calculation has to be made before other calculations because the mass of the antivibration cable impacts other calculations. Furthermore, all the busbars' strain components have to be calculated, which includes vertical load, horizontal load and the load caused by dynamic forces. The vertical load is the result of the mass of the busbar system tubes themselves, possibly the mass of the inserted antivibration cable and other masses of the connecting elements of the busbar disconnectors.

The horizontal load is the result of the force of the horizontal wind straining this way the tubes of the busbar system. The load caused by the dynamic forces is the result of the short circuit forces that don't last long, but have to be taken into account since they put a significant strain on the busbars, and they primarily depend on the gap between phases and the initial three-pole short circuit current. By adding these three strain components, the total strain of the busbars is obtained for the worst-case scenario (short circuit) and it has to be less than the elastic limit of the tubes used for the busbar system. Further, it is necessary to carry out the calculation of the maximum sagging of the tubes in normal operation, but also for a short circuit. The maximum sagging of the busbar for normal operation is relevant for the design of the tubes of the busbars and it has to be less than:

$$f_{nmax} = \frac{l}{100} \tag{1}$$

In this case, the bay width is 21 m, which means that the busbar sag mustn't be greater than 21 cm. Even though the busbar sag reaches the maximum value in the case of a short circuit, its value is not relevant for the design of the tubes of the busbars, yet it can be a useful information. Finally, the maximum forces on the busbar supporting equipment (insulators and the connecting elements) have to be calculated, and they must withstand all the loads that they may be exposed to in normal operation, but also in case of a short circuit. The load on the supporting insulators is the result of the weight of equipment it is supporting, load due to wind and load due to a short circuit. The maximum load on the supporting insulators must be less than its breaking strength.

4. SPOJNI VODOVI 400 KV I 220 KV TRANSFORMATORSKIH POLJA

4. CONNECTION LINES OF 400 KV AND 220 KV TRANSFORMER BAYS

Since the new 400 kV =C7 transformer bay fits into the existing 400 kV plant, the existing 400 kV busbar system design should be kept (double busbar system with bypass isolator). For the purposes of equipping the new transformer field =C7, the existing portals P1 and P2 (portals for suspension of connection lines for the bypass of circuit breaker) have to be elongated for a bay width (21 m). The existing portal crossarms have to be elongated and connected to the new individual portal leg. The 400 kV connecting line that serves for bypass of circuit breaker is added to the new crossarms of the transformer bay =C7. Also, for the purpose of connecting the autotransformer to the 220 kV field =D13, a new portal, marked P3, has to be constructed on the other side of the circular road of the transformer bay =C7. This portal serves as the second anchor point of the 220 kV connecting line for connecting the autotransformer -AT3 to the 220 kV cable. This means that the new crossarm of the P1 portal which is situated above the new autotransformer -AT3 is loaded by the 400 kV connecting line on the one side, and by the 220 kV connecting line on the other side. The new connecting lines are suspended through the appropriate insulating chains from the new crossarms of the portal. In order to ensure the safety and reliability of the operation, it is necessary to carry out calculations regarding connection lines in order to prove that they are appropriately designed. When designing the connecting line, the maximum current load of the connecting line in normal operation, the thermic influence of the short-circuit current, the electric field intensity on the surface of the conductor of the connecting line and the dependency of the cable sagging, temperature and mechanical strain of the connecting wire have to be taken into account. Finally, calculation of the tensile forces and the safety gaps during short circuit have to be calculated, which are later to be used as the base in selecting the appropriate insulating chains.

The maximum current load of the connecting line depends on the type and cross section of the wires used for the connecting line. It has to be greater than the nominal current of the transformer bay which is defined by the power of the transformer and is 650 A. The maximum current load can be hand calculated by taking into account the heat input by the solar radiation, heat dissipation through radiation from the wire and through convection from the surface of the wire and the specific resistance of the wire at maximum operation temperature (most often 80°C), but this calculation often gets circumvented and the value of the maximum current load is taken directly from the wire manufacturer's catalogue. The 400 kV connection line is executed with two aluminium-steel cables in a bundle with the cross-sectional area of 490/65 mm^2 and the total maximum current load of 1,920 A.

The condition of the thermic influence of the short circuit current represents the permitted short-circuit current density that is permitted to pass through the line without its properties being jeopardised. Mathematically, this condition is noted as:

$$S_{th} \leq S_{thr} \cdot \sqrt{\frac{T_{kr}}{T_k}} \qquad (2)$$

where:

- S_{th} - short-circuit current density of the wire

- S_{thr} – permitted short-circuit current density of the wire

- T_{kr} – nominal duration of the short circuit

- T_k – actual duration of the short circuit

The electric field intensity on the surface of the wire has to be below the critical value of the electric field intensity, which is $E_{Ekr} = 21{,}1\ kV/cm$. If this prerequisite has not been met, the strong electric field around the wire will cause air ionisation around the surface of the conductors and the conducting part of the insulating chains that is manifested by a purple-blue light and is called corona. This phenomenon represents electricity loss and is to be avoided.

The mechanical calculation of the connection lines encompasses the calculation of the static tensile forces, strain and sagging due to own mass and additional weights. Sagging and strain are a function of temperature. With temperature rising, the sagging increases, while strain decreases due to thermal expansion of the wires. This calculation is based on solving the sagging curve, and is most often performed through appropriate computer programmes. The solution is in the form of a table showing the dependency of the wires sagging and the static tensile force on the wire temperature. With such a table, the calculation of tensile forces and safety gaps during a short circuit can be performed, as detailed in the HRN EN 60865-1 [6] standard. In case of a short circuit, high currents flow through the conductors. Those currents cause certain forces in the conductors that result in a physical displacement of the conductors. The forces caused by the short-circuit currents are divided into:

- The tensile force caused by the swing of the conductor F_t
- The tensile force caused by the drop of the conductor F_f
- Forced caused by the pinch effect F_{pi}

The tensile force caused by the swing of the conductor occurs as a result of mutual electromagnetic forces between two conductors that current flows through. An attraction force occurs between two parallel conductors that current flows through in the same direction, while a repulsive force occurs between two conductors that current flows through in opposite directions. As a result of high short-circuit currents, the attractive force between the conductors of the connection line becomes much stronger compared to the normal operation and causes wires to move apart which in turn causes strain in the wires and reduces the voltage clearance between the conductors of different phases. After the short-circuit state stops, the conductors return to their original, stationary state, and the force that occurs when the wires fall to their original position is called tensile force caused by the drop of the conductor. Except for these two forces, there is also a force caused by the pitch-effect that occurs between two or more subconductors of the same phase of a connection line. The relevant force in designing insulating chains of an individual connection lines is the maximum force of the operating strain obtained by the calculation of the tension forces caused by a short circuit.

5. IZBOR I DIMENZIONIRANJE PRIMARNE OPREME TRANSFORMATORSKIH POLJA 400 KV I 220 KV

5. SELECTION AND DIMENSIONING OF PRIMARY EQUIPMENT OF TRANSFORMER BAYS 400 KV AND 220 KV

The high voltage equipment, from the current and voltage strain standpoint, must satisfy the conditions of normal operation and the conditions in case of a short circuit. From the voltage strain standpoint, the equipment must satisfy the conditions of the highest voltage in normal operation and the required values of the tolerable test voltage for the full insulation level. The choice of the 400 kV and 220 kV transformer bay primary equipment is carried out based on the on-site requirements as defined by the specifications [7]. On-site requirements include:

- Power grid nominal voltage
- Highest voltage in normal operation
- Rated switching impulse withstand voltage of the 250/2 500 µs form
- Rated withstand alternating voltage 1 min, 50 Hz
- Rated lightning impulse withstand voltage of the 1,2/50 µs form
- Nominal frequency
- Initial three-pole short circuit current I_{k3}

- Short-circuit surge current I_{din}
- Short-circuit duration
- Transformer bay nominal current
- Nominal short-term breaking capacity

All of the selected primary equipment must meet all the requirements at the installation site referring to it. The requirements for high-voltage circuit breakers stipulate that the nominal current of the circuit breaker must be greater than or equal to the nominal current of the transformer bay, that the nominal breaking capacity of circuit breaker must be greater than or equal to the nominal short-term breaking capacity, and that the nominal inrush current of the circuit breaker must be greater than or equal to the short-circuit surge current. Basic requirements for the high-voltage isolators stipulate that the nominal current of the isolator must be greater than or equal to the transformer bay nominal current, that the short-term withstand current must be greater than or equal to the nominal short-term breaking capacity, and that the isolator nominal surge current must be greater than or equal to the short-circuit surge current. Basic requirements for high-voltage instrument transformers stipulate that the nominal current of the primary winding can be up to 20% less than the transformer bay nominal current, that the short-term withstand current must be greater than or equal to the nominal short-term breaking capacity, and that the nominal surge current of the instrument transformer must be greater than or equal to the short-circuit surge current.

When selecting a surge arrester, the basic characteristics relevant to its appropriate selection are the continuous operating voltage U_c, rated voltage U_r, nominal discharge current in the 8/20 μs form, the nominal specific energy capability and the surge arrester class. For surge arresters mounted between a phase and earthing in a power grid with an efficiently grounded neutral point, the basic requirements for the selection of the continuous operating voltage is for its peak value to be equal to or greater than the peak value of the highest power grid phase voltage. Usually, it is the highest power grid voltage Um that is considered the peak value of the line voltage. Hence, continuous operating voltage of surge arrester must meet the following formula:

$$U_C \geq \frac{U_m}{\sqrt{3}} \tag{3}$$

The nominal voltage of surge arrester is the maximum allowed effective voltage value, of the nominal frequency and the limited duration of 10 s. Surge arrester nominal voltage U_r is selected based on the possible temporary overvoltages at the location of the surge arrester's installation. The temporary overvoltages are oscillatory overvoltages between a phase and the ground or a phase and a phase in a certain point of the power grid. They are characterised by the oscillation amplitude (U_{TOV}), duration (t_{TOV}) and frequency. Since the temporary overvoltages have different durations and amplitudes, it is desirable to express them through the equivalent temporary overvoltages with the amplitude Uekv and the duration of 10 s:

$$U_{ekv} = U_{TOVi} \cdot \left(\frac{t_{TOVi}}{10}\right)^m \tag{4}$$

Where:

- U_{ekvi} is the amplitude of the equivalent ith temporary overvoltage
- U_{TOVi} is the amplitude of the ith temporary overvoltage
- t_{TOVi} is the duration of the ith temporary overvoltage
- m is a coefficient with the value between 0.018 and 0.022

The basic requirement that needs to be met is for the nominal voltage of surge arrester to be greater than or equal to the maximum possible temporary overvoltage at the location of the surge arrester's installation in the plant, which means that the nominal voltage of surge arrester has to be:

$$U_r \geq U_{ekv} \tag{5}$$

Also, the location of the surge arrester installation is determined by the object that the surge arrester needs to protect. Surge arresters have a defined protecting area, but in practice it is always best for the surge arrester to be installed as close as possible to the protected object (most often a transformer).

6. UZEMLJENJE
6. GROUNDING

Devices and equipment being installed within the scope of this expansion get connected to the expanded grounding system. All the metal masses, such as stands of the new primary and secondary equipment as well as all the other metal masses have to be connected to the grounding system. The new grounding system gets connected to the existing grounding system so that the existing grounding, along with the new grounding forms a solid galvanic unit. The construction of the grounding system itself has the form of a grid 5 to 15 m in size which is connected to the existing main grounding system in multiple points. The existing main grounding system in substation 380/220/110/10 kV KONJSKO is executed as a mesh, double grounding system (higher and lower grounding system). The lower system is executed by virtue of copper tapes 30x3 mm driven in to the depth of 0.7 m, while the higher grounding system is executed through FeZn tapes 40x5 mm driven in to the depth of 0.6 m.

The grounding grid in the area of the =C7 and =D13 bays is executed through a copper rope 120 mm^2, driven in to the depth of 0.8 m. The soil around the grounding rope has to be well conductive packed earth (humus), 100 mm under the rope and 200 mm above the rope, while the rest of the trench gets filled with the earth that was excavated. All the main grounding system junctions need to be connected with appropriate clamps, depending on the grounding system construction.

The high-voltage devices get connected by a grounding rope to the stands they are mounted on, while the stands of all the high-voltage devices get connected to the new mesh main grounding system by way of a double rope which is connected to the stands of high voltage equipment by compressive clamps. Connecting the surge arresters and grounding the autotransformer neutral point -AT3 will be executed by way of deep connection to the ground (3m-long Cu rods), connected to the main grounding system mesh through a Cu rope od 120 mm^2. For the purposes of protection, control, signalisation and measuring, new secondary equipment have to be installed in the existing relay building KU-2. All the enclosures have to be connected to the existing grounding system inside the existing relay building.

By correctly designing the grounding system, the acceptable distribution of the potential inside and outside of the TS Konjsko plant as well as the acceptable touch and step voltages are ensured, which is vital in protecting human life.

7. GROMOBRANSKA ZAŠTITA
7. LIGHTNING PROTECTION

The lightning protection can be carried out in multiple ways, and one of them is by using lightning rods. This method of lightning protection is economical, and it doesn't jeopardise the plant safety because malfunctions probability on the installation itself is miniscule. Principle of the protection by lightning rods is that through a certain distribution of lightning rods in the plant, protective areas are created between the rods, which renders the whole plant protected from lightning.

While calculating lightning protection protective areas, elements that need to be protected from lightning need to be known. The busbars and connection lines are usually the highest elements in a plant that get protection from lightning, while the rest of the power equipment follows. This means that, if it can be proved that the highest element of a part of the plant is efficiently protected, then so are all the elements below it.

The elements that need lightning protection are:

- 400 kV connection line for bypass of circuit breaker
- 220 kV connection line for connecting autotransformer to 220 kV cable
- 220 kV cable terminal
- 220 kV busbars
- 220 kV connection line over auxiliary busbar

Correctly designed lightning protection ensured an effective lightning protection, but doesn't provide full plant protection due to unpredictability and lack of understanding of lightning. The procedure of determining lightning bars protective areas is prescribed by the HRN EN 60305 standard [7].

8. ZAKLJUČAK
8. CONCLUSION

This paper encompasses the field of the electrical power engineering with regard to the design of primary electrical circuit in high-voltage substation, as well as grounding and lightning protection of the primary electrical circuit equipment. The calculation of the tubular busbars, connection lines, grounding and lightning protection serve as a proof of the correct plant system design, where all of them have to be aligned with the relevant standards for the individual part of the plant. All the calculations have to show significant buffer value in comparison to critical cases which is a very important fact from the design standpoint for the purpose of ensuring a high level of safety and reliability of the plant.

Based on the performed calculations, the selection and design of other parts of the plant within the scope of the project was possible, such as the steel structures and the foundations, as well as the design of the secondary circuits for protection, measurement, signalisation and management.

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9. REFERENCES

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AUTORI · *AUTHORS*

• **Marko Mićanović** - Born 1997, in Zagreb. Graduated from the Zagreb University of Applied Sciences in 2023. Has worked in RAVEL d.o.o. since 2020 dealing in the design of high- and low-voltage electrical power plants

Korespondencija · ***Correspondence***

marko.micanovic@ravel.hr

• **Krešimir Meštrović** - Unaltered bio can be found in Polytechnic & Design Vol. 1, No. 1, 2013.

Korespondencija · ***Correspondence***

kmestrovic@tvz.hr