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Application of fully automated centralized voltage regulation in transmission system operation management

Renata Rubeša, Marko Rekić, Zoran Bunčec, Tomislav Stupić

***Summary* — The influence of wind farms, inclusion of distributed energy and the energy market has a large impact on the voltage profile in a transmission system. The Croatian Transmission System Operator HOPS has implemented VVC (Volt Var Control) system which was one of the subprojects included in the EU co-founded Sincro. Grid smart grid project that was financed by the EU CEF fund. The main goal of the project is to raise voltage quality in the transmission network. VVC system is an optimal power flow-based application which calculates the optimal solution regarding the desired objective function, available control variables and a defined set of constraints. To achieve the calculated optimal power system state, control of field devices is included in the process of optimization by shifting tap changer positions or changing setpoint values of reactive power injection. Voltage and reactive power constraints are set accordingly to available regulating devices included in the optimization. The lack of automatic coordination of reactive power resources motivated this work for implementing an advanced VVC for real time control of reactive power in partially automatic and fully automatic (closed loop) mode using the optimal power flow (OPF) algorithm. Due to its complexity, the closed loop approach of reactive power regulation is rarely used in the TSO community and the HOPS is one of the first TSOs that implemented regulation in such manner. Except fully automatic mode of operation, VVC can be used in semi-auto or manual mode. For a successful implementation several safety algorithms are implement to avoid many unwanted situations in the power system such as voltage breakdown, overloading of regulating equipment and similar.**

***Keywords* — Volt Var Control – Optimization - Transmission Network - Optimal Power Flow - Voltage Profile**

I. Introduction

Transmission System Operators are responsible for the security of operation, facilitation of regional markets and integration of renewable energy sources (RES). Thus, development of grid infrastructure, supporting technologies and mechanisms are key elements for proper and timely integration of RES. In recent years, the Croatian power system has been increasingly challenged by contradictory influences impacting the operation of the power systems:

- Support of RES integration to meet the EU targets,
- A lower electricity consumption due to the economic crisis,
- A growing lack of centralized electricity production for electric system support,
- The high interconnectivity between the neighboring control zones.

Consequently, the Croatian transmission System Operator HOPS observes growing issues in keeping the voltage profile of the transmission network inside the prescribed limits. This issue has been addressed by implementing a power system voltage and reactive power regulation scheme on a national level which would allow more RES generation to be connected to the transmission and distribution power systems. Power system voltage and reactive power regulation schemes can be generally classified as hierarchical or as centralized voltage regulation systems. Ways of implementing these two regulation systems vary greatly from one TSO to another [1]. Hierarchical regulation rests on implementation of three temporally and spatially separated control levels: primary, secondary, and tertiary control [2]. Primary voltage regulation automatically implies response of local voltage regulators, primarily synchronous generators and onload tap changers in substations. Secondary regulation refers to voltage regulation within a defined zone, while tertiary regulation is carried out on regional or national level. The problem is usually seen as a static problem, whose solution is identical to an open-loop optimization base volt/var management [3]. In HOPS the implemented voltage and reactive power regulation scheme, referred to as tertiary control on a national level and is based on an optimal power flow (OPF) type algorithm. Addressing the issue of implementing such a complex system in a closed loop operation in a TSO led to several open questions:

- The definition of voltage optimality accompanied with regional contributions for a system wide performance criterion.
- Improvement of voltage profile in particular regions experiencing shortage of voltage support [3].
- Voltage profile and stability is mainly a local issue, but some of major large network disturbances and blackouts were caused by voltage stability issues. Apply the automatic operation of the voltage and reactive power regulation scheme ensuring safe and reliable network operation.

This paper will elaborate on these questions and how they were practically solved in HOPS in scope of Sincro.Grid VVC project.

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II. Volt Var Control System Design

A. Primary and tertiary regulation scheme

Most transformers (220/110 kV and 400/110 kV transformers) are equipped with an onload tap changer (OLTC) that can change the ratio of the transformation in operation and thus control the voltage on the regulated side of the transformer. Local voltage regulators on transformers typically regulate the lower voltage side of transformers.

Unlike local voltage regulators, the central Volt and Var Control (VVC) system has insight into the entire network and the ability to manage voltages throughout the power network. The calculation of the optimal power flows of the central optimizer is defined by the objective function and the set voltage limits. The objective function of the VVC system is set to minimize the operating losses in the system [4]. The basic algorithm of the VVC function is the optimization algorithm of the OPF function based on the interior point method. The execution of the VVC output (is executed by the SCADA/EMS system installed in HOPS. The ability to manage voltages in the power network largely depends on the available objects in the optimization. In the case of VVC systems in HOPS, it is possible to control a total of 28 power transformers and 2 variable shunt reactors (facilities owned by TSO) to which VVC system can issue control orders (with or without the intervention of the dispatcher\operator). Also, 11 production units (5 generators in Hydro Power Plants, 3 generators in Thermal Power Plants and 4 generators in Wind Power Plants) are included in the optimization calculation. For the VVC calculation to be successful and the control orders ready to be issued to the facilities, the optimal results of all voltage values must be within the defined limits. Therefore, it is very important, depending on the involvement of objects in the optimization, to define voltage limits for individual nodes and analyze the voltage sensitivity of individual objects included in the optimization to avoid large movement of individual objects in optimization.

Table I

Comparison of local voltage regulators and central voltage and reactive power regulation scheme

	Local voltage regulation	VVC system
Voltage Control	Voltage control only on the regulated bus	Voltage control of the entire network
Regulated bus	Only one regulated bus	All the buses in the network with respect to voltage limits
Regulation mode	Automatic maintenance of the selected voltage setpoint value only on the control bus	VVC calculation based on available devices in optimization while meeting the objective function to reduce losses. After the calculation, the set-points can be sent with the approval of the operator\dispatcher or automatically without the confirmation of the operator\dispatcher
Loss optimization	Not implemented	Supported, there is insight into voltage conditions throughout the network. After calculating the optimal power flows, the calculation of the difference in losses before and after optimization is visible.
Device control	Controls only the OLTC on one object (in case of parallel operation of transformers, mutual communication of regulators on parallel transformers is possible)	Manages selected objects that participate in optimization and have the ability to manage from the VVC system

B . VVC system design

The VVC system consists of the transmission network model, modelled in the accurate AC manner. The model is imported via the Common Information Model (CIM) standard from the production SCADA/EMS system. The real time measurements and breaker status are imported via IEC 61870-5-104 protocol cyclically with a time interval of one minute [6]. The VVC system runs a state estimation process, and the results are the base case for the OPF process. OPF results (setpoints of control variables) are transferred back from the VVC system to the production SCADA/EMS system via ICCP protocol and dispatched to field devices. The system presented on Figure 1 can be run in semi-automatic mode (the dispatcher sends the controls manually to field devices from the SCADA/EMS system) or in the automatic i.e., closed loop control mode where no dispatcher intervention is needed, and the set points are automatically sent to field devices after each OPF execution. In closed loop control mode, the OPF function can be executed every 15, 30 or 60 minutes.

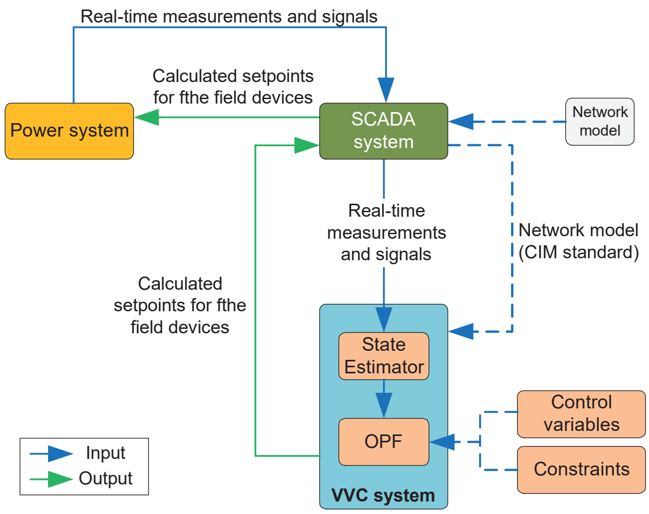

Fig. 1. VVC system design

C. Voltage constraints

Initial voltage low an upper limits or constraints for the 400, 220 and 110 kV voltage levels are defined to be compliant to the COMMISSION REGULATION (EU) 2017/1485 SOGL (System Operation Guidelines) documents and Network Codes. The values of these constraints are defined in Table II. VVC has more rigorous voltage limit compared to the limits from the Network Codes. This provides a safer voltage band within the voltage and can fluctuate due to changes in the network (such as the change of the topology) between two consecutive optimization cycles or runs.

Table II

Voltage constraints in the VVC system

Voltage level [kV]	Lower limit in VVC [kV]	Upper limit in VVC [kV]	SOGL limits [kV]
110	105	122	99 - 123
220	210	244	198 - 246
400	390	418	360 - 420

Figure 2 bellow shows the graphical representation of 220 kV node voltages in one region of the transmission network, during a 4-day time span when VVC performed the optimization cycles (left side) and the equally long period without reactive power optimization (right side). In the period without optimization (right side) of the figure only local (primary) voltage regulation was active.

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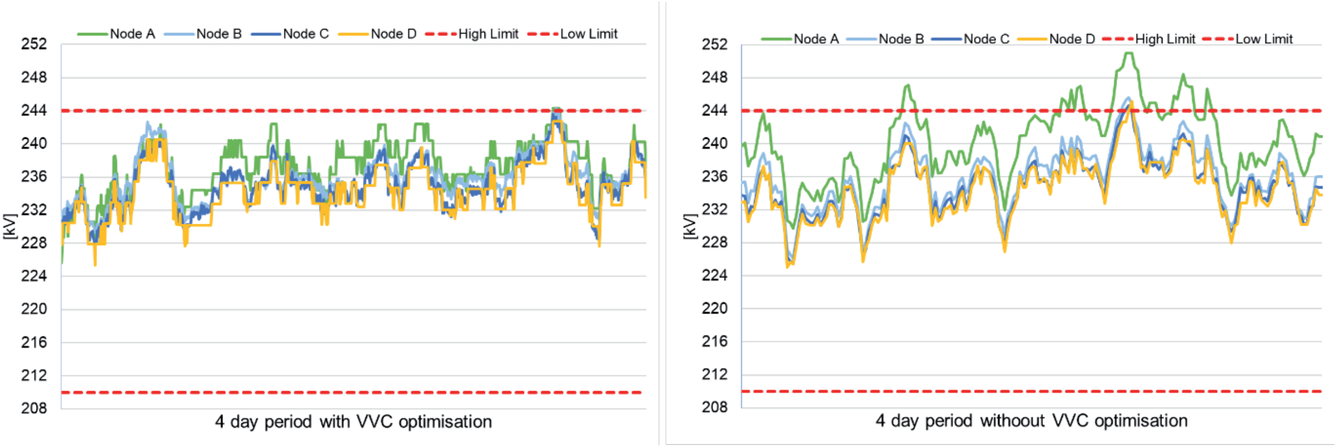

Fig. 2. Node voltages in 4-day period with optimization (the left side) and without optimization (the right side)

It can be clearly seen that during the VVC optimization cycles, node voltage magnitudes were all the time within defined limits, unlike the period when the VVC was not in the operation and the node voltage was outside defined limits. The VVC system keeps the node voltage magnitudes close to the high limit value, which is also a confirmation that the VVC performs a defined objective function to reduce MW losses. By increasing voltage level, the amount of current flow through network elements is consequently reduced, which leads to a consequent reduction of active power losses.

As mentioned before, the VVC algorithm tries to reduce active power losses by keeping voltages close to the high voltage limit, so during the testing, VVC raised node voltages in the system when that was feasible and consequently reduced the active power losses in the system.

Figure 3 shows a radar diagram of 220 kV and 400 kV node voltages in the power network before the implementation of VVC optimal setpoints and the same node voltages after the implementation of the VVC optimal setpoints. A heat map of network before and after the optimization cycle is also given for the same example in Figure 4.

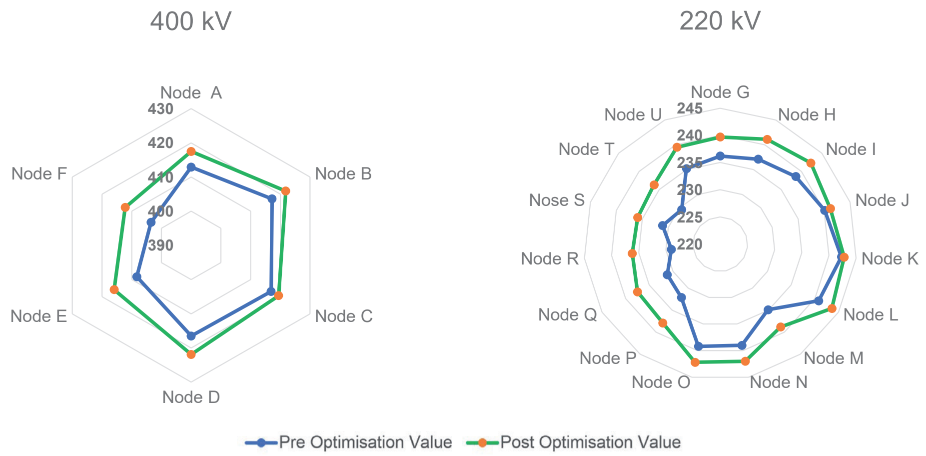

Fig. 3. Radar diagram of pre and post optimization voltages

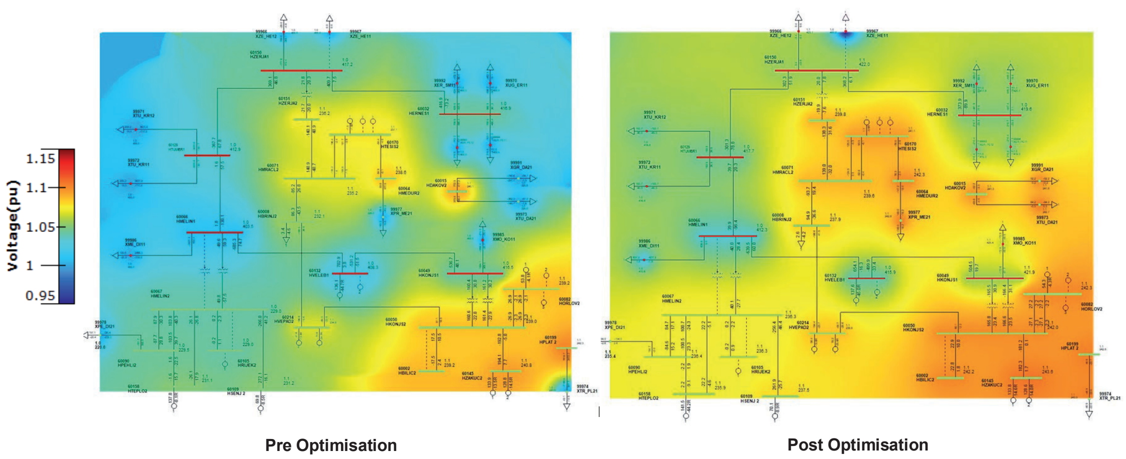

Fig. 4. The heat map of node voltages before and after performing the optimization

The graphs above show that VVC increased the voltages in the part of the network where it was possible and thus equalized the voltage profile in the transmission network, which can be seen from the radar diagram. The radar diagram of the optimal power network condition has a rounder shape as well as more uniform contours on the heat map after performing the optimization cycle.

However, for some nodes, specific, softened constrains had to be applied. This had to due to the fact that particular power network regions experience shortage of voltage support, i.e., the optimization solution violates constraints that have no controls electrically sensitive to them. In this case the solution is infeasible, or if the controls are marginally sensitive, the solution suggest to enforce large, uneconomical control shifts from their original value. In HOPS this issue is overcome with two solutions:

- Prior the optimization process (OPF) perform a **sensitivity analysis** in order to determine the range of influence of control variables to voltage magnitude. The sensitivity analysis provided a list of insensitive nodes to changes in control variables and divided the transmission network into control zones. The result of the sensitivity analysis divided the HOPS power network into 8 optimization zones shown in Figure 5.

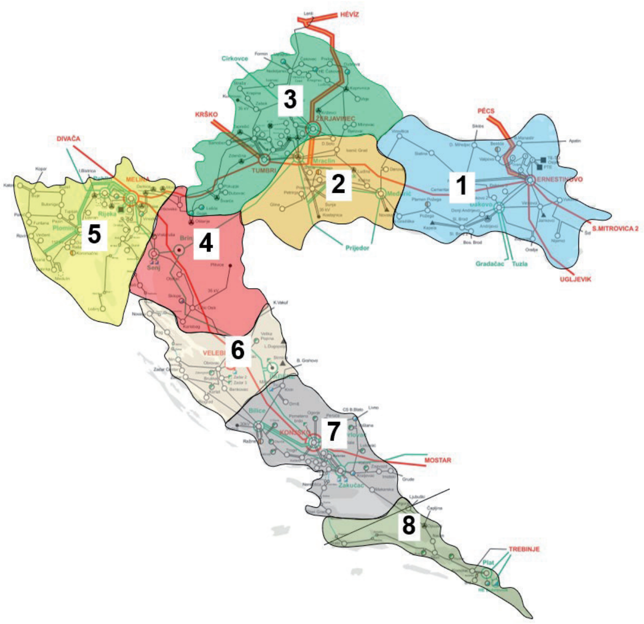

Fig. 5. Croatian transmission network and division in to 8 optimization zones

All the zones participate in the OPF problem simultaneously, but the operator\dispatcher has the possibility to exclude zones from the calculation if the zone has insufficient compensation resources.

- After the OPF calculation, check the number of individual control variables shifts and automatically block sending set point values to field devices in case the calculated optimal set points of control variables have large deviations compared to base case positions. This situation will trigger an alarm and such setpoints will not be sent automatically. Setpoints can be send in semi-auto operation mode after the operator\dispatcher confirmation. The amount of deviation is set as a parameter by the operator\dispatcher (for example 3 control shift deviation for transformer and VSR tap position and 15 MVAr for reactive power production for production units).

This two-step approach limits the engagement of control variables prior and after the optimization process to preserve the primary equipment to undergo uneconomic shifts which have no or minimal positive impact on the voltage profile.

III. VVC Security Mechanisms

Implementing such a complex system in a transmission system, implies the need to constantly monitor the entire process consisting of receiving measurements, signals and indications from the network, availability indications form devices included in the optimization, control of the OPF calculation and configuration, display and verification of result, sequencing, and coordination of commands. A set of automatic security controls had to be implemented to prevent sending of unfeasible or unreliable set points to filed devices without operator\dispatcher intervention. In case any of the below security mechanisms activates an alarm is triggered an the VVC execution is automatically stopped.

A. State estimation quality

The state estimator is the base case solution for the OPF algorithm. The state estimator gives the most likely state of the network which will be further used in power flow and OPF calculations for the purpose of calculating optimal set points. The performance of the state estimator calculation is evaluated by the state estimation quality index. If the state estimation quality index is below a user defined threshold, the VVC function will not start so the possibility of poor quality OPF calculation will be avoided.

B. Control of OPF calculation quality

In order for the solution of the OPF function to be sent to field devices, the OPF solution must be calculated within the defined error tolerance otherwise it will not be possible to send set points. This security mechanisms monitors the difference between the calculated pre and post optimization losses which must be within a predefined amount.

C. Emergency stop

One of the main functions for the secure operation of the VVC system is the emergency stop function. The function enables operator\dispatcher to immediately stop the sequence of commands issued to field devices in case of undesirable situation with the execution of the set points or there is a large disturbance in the network. The execution of the optimization cycle can be stopped in a particular transmission network region by dispatcher\operator in Regional control center (RCC) or by dispatcher in National control center (NCC) for particular or entire network. The emergency stop function for transformers and variable shunt reactors will automatically stop the process shifting the tap changer position while for the power plants it automatically sends a set point for power factor = 1 to generators included in the optimization.

D. Monitoring of the devices included in the optimisation

All-important measurements, signals and indication from devices included in the optimization are continuously monitored to react immediately due to a certain change on them. If there is a loss of communication, internal errors on the device, alarms, changes in the mode of operation or similar, the same device will be excluded from the VVC calculation and no setpoints will be sent to this device. Also, if one of parallel transformers is unavailable, none of parallel transformers will be used in the optimization.

E. Monitoring and control of VVC setpoints execution

During the execution of the VVC function order and duration of execution, availability of the devices in the optimization, etc. are monitored. In this way it prevents the system from being brought into an unwanted state. Due to unexpected changes in the network

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such as switching off or communication unavailability of the devices in the optimization or similar, VVC will immediately stop the execution in that region and prevent the possible occurrence of a dangerous situation in the network.

IV. Setting up of the Optimal Power System State

The first step in implementing the VVC results is to switch off the local automatic control on individual objects in the optimization, i.e., to give the regulating control of individual objects to the VVC system. In the first run of the optimal power flow algorithm, a larger number of shifts in control variables occurs as a result the control variables now move in a coordinated manner to achieve the target function i.e., to reduce the operating losses in the system. Part of the test results is shown in Table III for two consecutive days of the field tests. The test started in the morning hours The delta shift value shows the total number of shifts of tap changer position (transformers, VSR) from the initial value. The initial value in the first run of the VVC algorithm is the value inherited from the situation while the local (primary) control was active. Delta shifts for the following runs is the total number of shifts of tap changer position (17 transformers, 2 VSR) from the previous run. The number delta losses show the difference between the base case losses and the losses calculated after the execution of all controls. The losses are in each run reduced compared to the initial or previous value, but the most beneficial part is the equalization of the voltage profile and improving the overall voltage situation.

Table III

VVC system field test data

WC run	1st run	2nd run	3rd run	4th run	5th run	6th run	7th run	8th run	9th run
1st day	10:42	11:42	12:42	13:42	14:42	15:42	16:44	17:51	18:42
D shifts	39	5	8	0	16	9	12	7	4
D losses [MW]	-0.952	-0.523	-0.818	-0.913	-0.515	-0.535	-0.363	-0.296	-0.309
2nd day	-	11:37	12:40	13:42	15:13	16:37	17:54	-	-
D shifts		16	8	5	2	4	8		
D losses [MW]		-1.296	-0.911	-0.358	-0.857	-0.801	-0.836		

Although the goal of the OPF function is to minimize an objective function, in this case the power system active losses, the OPF function also must satisfy the power system physical and operational constraints. Satisfying the constraints, i.e., voltage constraints, takes precedence overachieving the highest degree of optimality. The objective function of minimizing losses acts in the opposite direction with the algorithm requirement to keep the node voltages in prescribed limits. Accordingly, the system losses after the VVC run might be higher than in the initial situation. This case usually coincides with the daily load profile. During the day, the power system is more loaded than in the evening or at night. Load changes that occur at night and in the morning are highly reflected in the change of voltage profile. Therefore, the VVC system during the day period did not propose major control variable shifts as in the night period or in the period of a sharp drop and increase in load. The changes in the control variables were logical, compensating for the change in voltage because of the change in load.

V. Changing of Control Variables During VVC Operation

The voltage profile changes during the day and the change depends on the conditions in the network. Observing the voltage profile, correlation with the daily load profile can be noticed, i.e., in the reduced load period the voltage is higher, and in the period of increased load voltage is lower. This is a usual occurrence in the network. VVC in the optimization process tried to correct these changes in the voltage profile, i.e., in the specific periods of load change during the day a higher number of changes in control variables were made to successfully compensate the change of the voltage profile caused by load changes in the network.

For the purposes of the analysis, a graphical presentation was made in Figure 6 below. It contains the average number of changes in control variables per hour per day during a multiday VVC trial run. The number of changes in the control variables in this figure refers only to changes of transformers and variable shunt reactors tap changers.

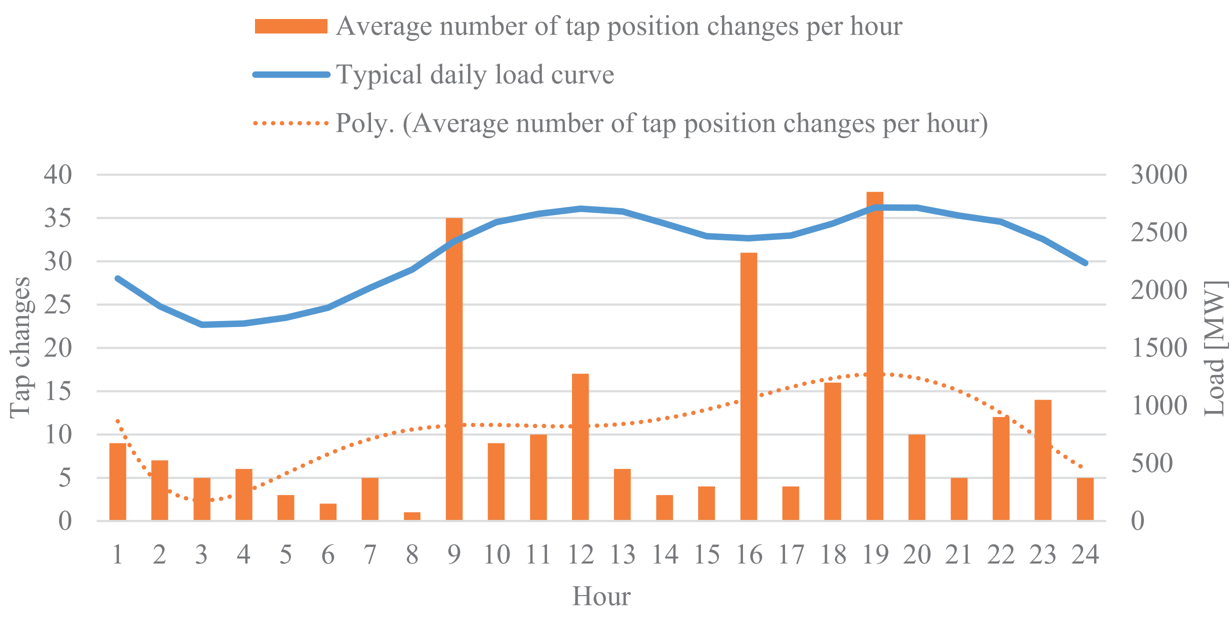

Fig. 6. Average number of control changes performed per hour and trend line of changes compared with daily load curve

Observing the graph above, higher number of changes in control variables are happening during the hours in which a significant change in load occurs. Also, a trend line of the change of control variables has been added, which clearly outlines the shape of the daily load diagram. This is one additional confirmation of how VVC successfully compensated the change in the voltage profile during the day and kept the voltage profile at the values most acceptable in terms of reducing active power losses in the system.

VI. Conclusion

The advantage of the VVC system implemented in HOPS is the possibility to operate the VVC in a closed loop without operator\dispatcher intervention. Due to its complexity, the closed loop approach of reactive power regulation is rarely used in the TSO community and HOPS is one of the first TSOs that implemented regulation in such manner. In conclusion, regardless of safety algorithms implemented to avoid many unwanted situations in the power system (such as voltage breakdown, overloading of regulating equipment and similar), transmission system operator should be aware of possible risks. For this reason, HOPS initially opted for safer approach and mostly used semi-automatic mode which is additionally under the control of the dispatcher\operator.

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