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IZVIRNI ZNANSTVENI ČLANEK

Finding the optimal tap positions of cascade-connected on-load tap-changer-equipped transformers

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Abstract. The paper proposes an algorithm for simultaneous finding optimal tap positions of cascaded on-load tap-changer (OLTC)-equipped transformers, operating on the primary and secondary level (110 kV/20 kV and 20 kV/0.4 kV substations). The algorithm developed to solve a constrained optimization problem uses differential evolution (DE) as an optimization tool. Its objective function minimizes the network power losses in a time-discrete operation and its penalization functions ensure that operational constraints (voltage profiles and line currents) are kept within the imposed limits. The algorithm operation is tested on a real power distribution network model consisting of three 20 kV feeders and two 0.4 kV networks supplied by a 110/20 kV substation and containing three OLTC-equipped transformers (one 110 kV/20 kV and two 20 kV/0.4 kV) for which the optimal tap positions are determined simultaneously. The impact of load modeling on the algorithm behavior is investigated.

Keywords: on-load tap-changer, differential evolution, loss minimization, load modeling

Določitev optimalnih nastavitev OLTC opremljenih VN/SN- in SN/NN-transformatorjev v kaskadi

V tem članku je predstavljen algoritem za istočasno določanje optimalnih nastavitev stopenj regulacijskih transformatorjev z možnostjo spreminjanja nastavitev pod obremenitvijo, vezanih v kaskado (110 kV/20 kV in 20 kV/0,4 kV transformatorji). Algoritem je formuliran kot omejen optimizacijski problem, ki temelji na iskalnem postopku diferenčne evolucije. Izraz za moč izgub omrežja v izbranem, časovno diskretnem obratovalnem stanju predstavlja kriterijsko funkcijo, ki jo minimiziramo v optimizacijskem postopku. S kazenskimi funkcijami je zagotovljeno, da so napetostni profili znotraj predpisanih mej, vodi pa niso termično preobremenjeni. Predstavljeni algoritem je testiran na modelu obstoječega omrežja, ki je sestavljen iz treh 20 kV izvodov ter dveh 0,4 kV omrežij, v katerih so prisotni trije regulacijski transformatorji z možnostjo spreminjanja nastavitev pod obremenitvijo. V prispevku je analiziran tudi vpliv modeliranja bremen na delovanje algoritma.

Ključne besede: regulacijski transformator, diferenčna evolucija, minimizacija izgub, modeliranje bremen

1 INTRODUCTION

The challenges that arise with the modernization of the power distribution networks (DN) can be classified into technical (e.g., issues regarding the power quality, protection, voltage control and stability), commercial (e.g., incentive schemes, investment return), and regulatory (e.g., regulatory policies) [1]. The voltage quality issue is one of the main power system concerns. A number of different approaches have been developed to mitigate the network-operation issues. A passive approach to solve the issue without much interference with the consumers or generation units, would be modification of the network topology, i.e., installation of new transformer substations, replacement of smaller cross-section cables, or installation of parallel-running cables. Though these solutions are technically simple to implement and bring an additional benefit in terms of reduced power losses, they carry high investment costs [2].

In traditional DNs, the voltage control is usually performed using on- or off-load tap-changers, switched capacitor banks, or step voltage controllers. On the other hand, advanced methods require an active assistance of various devices already connected to the network, provided that a proper communication infrastructure exists. Some of these methods include power generation curtailment of distributed generation (DG) units, such as photovoltaic (PV) systems during a low power demand, reactive power control (VAR compensation), area-based on-load tap-changer (OLTC)-coordinated voltage control, placement of inverters at DG sites, consumption shifting and curtailing, and energy storage [1].

OLTC is a mechanical device installed inside the transformer tank or mounted in a separate compartment. It enables voltage control and/or phase shifting by varying the transformer turn ratio under load without supply interruption. The change in the turn ratio is performed by adding or subtracting turns from the high-

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or low-voltage winding (usually the high-voltage winding, due to smaller currents). To enable the change, the transformer requires the control (or tap) winding connected to OLTC. The voltage between the taps is the step voltage, which is usually between 0.8% and 2.5% of the transformer rated voltage [3].

A review of voltage control techniques in networks with DG units using OLTC-equipped transformers is presented in [4]. The paper discusses the impact of DG integration on the OLTC control schemes. Reese et al. [2] presented the application of the OLTC-equipped distribution transformers and assessed the benefit of their usage in a voltage-control method. Moghaddam et al. [5] presented a practical method to manage cascade-connected OLTCs in networks with a bidirectional power flow. Tracking the active and reactive power changes in the medium- (MV) and low-voltage (LV) networks enables detection of the cause of the voltage variation to be followed by tap operation at a proper voltage level, to minimize the unnecessary tap operations and improve the voltage quality at the consumption point. A coordinated control method presented in [6] reduces the tap-changer-equipped transformer operational stress, shaves the DN peak load and decreases the network power losses at a high solar power penetration and active cooperation of energy storage systems. A comparative analysis of differential evolution (DE) and particle swarm techniques in reactive power and voltage control [7] to determine optimal tap-changer position shows that losses when using DE are slightly smaller. As DE required a considerably lower number of function evaluations the authors found it more viable for a potential real-time application in a control center where the computation time is most relevant. Therefore, a DE-based approach is selected as a base for the development of the proposed algorithm.

When operating OLTC-equipped cascade-connected transformers, graded time delays are often used to give OLTC at lower voltage levels enough time to deal with the voltage issues and reduce the number of unnecessary tap operations [5]. The approach in this paper differs from the above-mentioned one, as the main goal of the paper is to find optimal tap positions on demand in a given time-discrete point, for a given network configuration and power loading and generation values. The problem is formulated as the constrained optimization problem and is solved using a DE method. The used objective function minimizes the power losses at a certain time point. The penalization functions ensure that the voltage RMS values comply with the EN 50160 standard and the line currents are kept below the maximum limit values. This way, both the voltage control and network operation optimization in terms of power loss minimization are achieved.

The rest of the paper is structured as follows. Section 2 proposes a procedure to find optimal tap positions. Section 3 describes the implementation of the proposed algorithm on a real DN model and investigates the impact of load modeling on the algorithm behavior. Section 4 gives the final observations and draws conclusions.

2 PROPOSED ALGORITHM

Figure 1 shows a flowchart of the proposed procedure for finding the optimal tap positions of cascade-connected OLTC-equipped transformers.

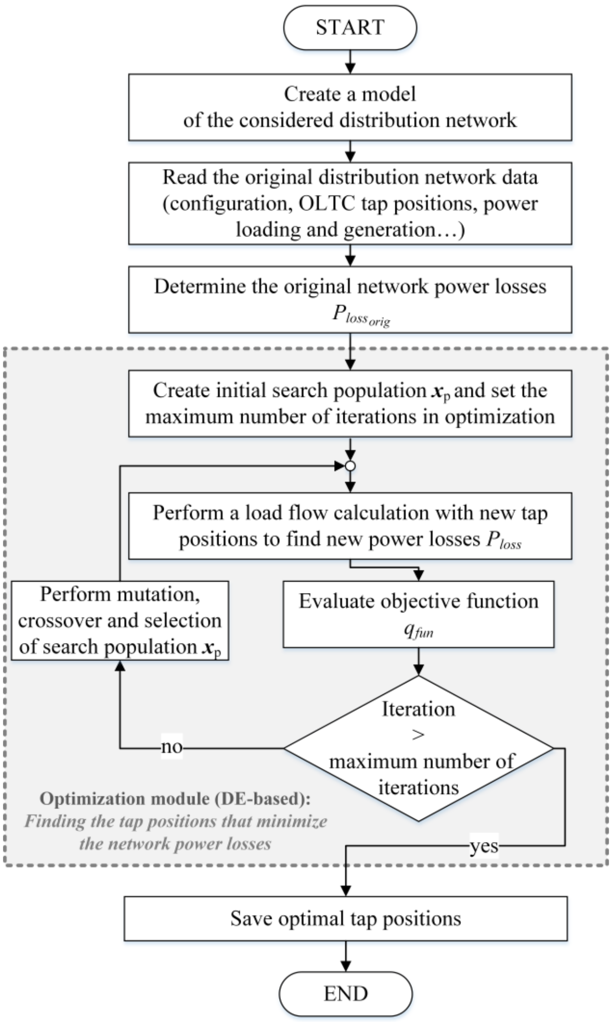

Figure 1. Flowchart of the proposed optimization procedure to find the optimal tap positions.

Firstly, a model of a considered network is created. The original network conditions, such as voltage profile and power losses, are evaluated using a load flow calculation. A backward-forward sweep method, modified to enable consideration of a meshed network configuration [8] is implemented. The data for every time-discrete calculation is given for the current network configuration, including distribution of the power consumed and generated in the network nodes at a given time point, load models describing the load voltage dependency, and the initial OLTC tap positions. Evaluation of the power losses for the original network conditions ($P_{loss_{orig}}$) is followed by the optimization module (see Figure 1). The optimal OLTC tap positions represented with a vector of search parameters $\boldsymbol{x}_p$ are determined within the optimization module, and power losses for new operation conditions (P_{loss}) are calculated. The optimization module and the objective function are discussed in detail in Subsection 2.1.

Figure 2 shows a line model of an OLTC-equipped MV/LV transformer substation. As the OLTC tap position changes, so do the base values of the voltage U_{baseLV} and impedance Z_{baseLV} of the LV part of the network.

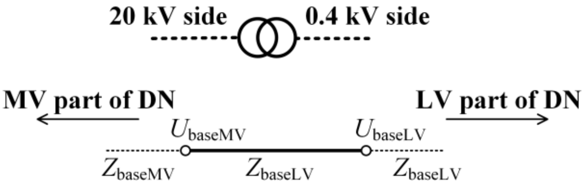

Figure 2. Determination of the corresponding MV and LV network voltage and impedance base values.

A per-unit system is utilized to consider the change in the voltage on the secondary side of an OLTC-equipped transformer and the part of the network it supplies directly. The LV network voltage and impedance base values applied to the nodes and branches, supplied by the OLTC-equipped transformer are modified to U'_{baseLV} (1) and Z'_{baseLV} (2).

$$U'_{baseLV} = U_{baseLV} + N_{TC_{pos}} \frac{A_{step}}{100\%} U_{baseLV} \tag{1}$$

$$Z'_{baseLV} = \frac{\left(U'_{baseLV}\right)^2}{S_{base}} \tag{2}$$

Value A_{step} is a percentage change in the voltage value per single step. $N_{TC_{pos}} \in \boldsymbol{N}_{TC_{pos}}$ is a vector element of possible OLTC tap positions $\boldsymbol{N}_{TC_{pos}}$ (3) and n_{TC} is the number of the possible tap positions.

$$\boldsymbol{N}_{TC_{pos}} = \left\{-\frac{n_{TC}-1}{2},\cdots,0,\cdots,\frac{n_{TC}-1}{2}\right\} \tag{3}$$

2.1 DE

DE is a simple, versatile, and robust heuristic approach for global optimization over continuous spaces, presented by Storn and Price in 1997 [9]. It is a population-based optimization mimicking the process of evolution in nature in order to minimize the possibly nonlinear and non-differentiable continuous space functions. Figuratively speaking, the process of finding a solution represents a competition in populations of parents and children, where the children will replace the parents if they are better than them, i.e., if the children yield a better value of the objective function.

The role of an OLTC-equipped transformer is to keep the voltages within the permissible intervals. This condition is a constraint function and the power loss minimization is the optimization objective function q_{fun} (4). The function minimizes the quotient of power losses of the original network and the network with changed tap positions. The penalty (p) is applied when an operational constraint is violated.

$$\min q_{fun} = \frac{P_{loss}(\boldsymbol{x}_p)}{P_{loss_{orig}}} + p \tag{4}$$

The search-parameter vector $\boldsymbol{x}_p$ is determined in the optimization module (5), where n is the number of OLTC-equipped transformers in the network. Parameters $x_{p,i}$ are then used to determine the OLTC tap position of each transformer.

$$\boldsymbol{x}_p = \left\{x_{p,1},\cdots,x_{p,n}\right\} \tag{5}$$

DE implementation is adapted to find the solution in a set of positive integers, corresponding to the number of the possible OLTC tap positions (n_{TC}). Each member of a search-parameter vector ($x_{p,i} \in \boldsymbol{x}_p$) is mapped from a set of real numbers to a set of positive integer values. These integer values represent a discrete value of a tap position of an OLTC-equipped transformer, i.e., an element of the vector $N_{TC_{pos}} \in \boldsymbol{N}_{TC_{pos}}$.

Specifically, the value of the search parameter ($x_{p,i}$) determined in the optimization module is included in the equation for the base voltage and impedance for the part of the network affected by a change in the tap position, as given in (6) and (7).

$$U'_{baseLV}\left(x_{p,i}\right) = U_{baseLV} + N_{TC_{pos}}\left(\left\lfloor x_{p,i}\cdot n_{TC}\right\rfloor + 1\right)\frac{A_{step}}{100\%}U_{baseLV} \tag{6}$$

$$Z'_{baseLV}\left(x_{p,i}\right) = \frac{\left(U'_{baseLV}\left(x_{p,i}\right)\right)^2}{S_{base}} \tag{7}$$

Therefore, parameter $x_{p,i}$ affects choosing the optimal tap position, i.e., the right integer from the set $\boldsymbol{N}_{TC_{pos}}$.

3 CASE STUDY

A real DN is used to test the proposed algorithm for finding the optimal tap positions of cascade-connected OLTC-equipped transformers.

3.1 Test site

Figure 3 shows a single-line DN diagram used for testing the proposed optimization algorithm.

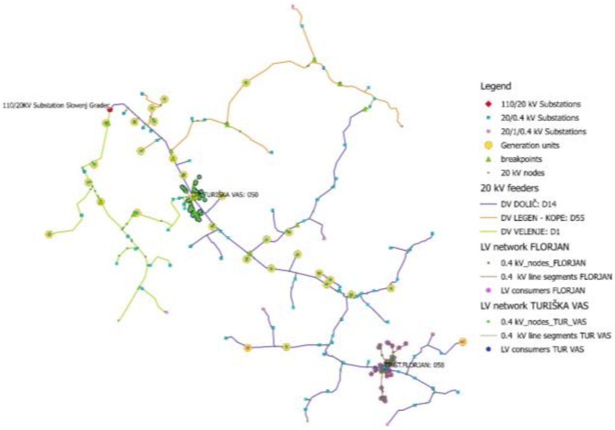

Figure 3. Single-line diagram of the tested network.

The MV part of the tested network comprises three 20 kV feeders, supplied by Slovenj Gradec OLTC-equipped 110/20 kV substation, comprising 297 nodes and 297 20 kV line segments. Two LV networks supplied by Št. Florjan and Turiška vas OLTC-equipped 20/0.4 kV transformer substations comprise 189 nodes and 187 0.4 kV line segments. The network configuration is assumed to be constant throughout the simulations (meshed with a single loop at the 20 kV level). There are 110 20/0.4 kV transformer substations and 129 consumers connected to the LV networks (61 in the LV network supplied by the Št. Florjan substation and 68 in the LV network supplied by the Turiška vas substation). 30 out of the 110 substations have their generation units connected on the substation LV side.

In the tested DN, three OLTC-equipped transformers are cascade-connected (one is placed at the Slovenj Gradec HV/MV substation and two are placed at the Turiška vas in Št. Florjan MV/LV substations). Their possible tap positions and impact on the network modeling, are given bellow. In the equations, the variables $x_{p,1}$, $x_{p,2}$ and $x_{p,3}$ are the elements of the vector of the search parameters ($\boldsymbol{x}_p$) determined using DE and are used to calculate the discrete values of the tap positions of the OLTC-equipped Slovenj Gradec, Turiška vas, and Št. Florjan substations, respectively.

1) **Slovenj Gradec 110/20 kV substation** (*voltage range ±16%, 1.33% per tap step, 25 tap positions)*

The voltage and impedance base values do not need to be changed as the transformer 20 kV busbar is the network slack node. Its voltage value in the per-unit system (U_{slack}) is for different tap positions determined using (8). The equation ensures that the first vector element of the parameters ($\boldsymbol{x}_p$) determined using DE from a constrained interval $x_{p,1} \in [0,1]$ gives the tap position, which is an integer number from a vector $\boldsymbol{N}_{TC_{pos1}}$ (9).

$$U_{slack} = U_{baseMV} + \boldsymbol{N}_{TC_{pos1}} \left(\lfloor x_{p,1} \cdot 25 \rfloor + 1 \right) \frac{1.33\%}{100\%} U_{baseMV} \tag{8}$$

$$N_{TC_{pos1}} \in \boldsymbol{N}_{TC_{pos1}} = \{-12, -11, \cdots, 0, \cdots, 11, 12\} \tag{9}$$

2) **Turiška vas 20/0.4 kV substation** (*voltage range of ±12%, 3% per tap step, nine tap positions*

The modified LV network voltage and impedance base values are determined from (11) and (12) by considering the tap position $N_{TC_{pos2}}$ (10). These base values are applied to every node and line segment of the LV network supplied by Turiška vas substation.

$$N_{TC_{pos2}} \in \boldsymbol{N}_{TC_{pos2}} = \{-4, -3, \cdots, 0, \cdots, 3, 4\} \tag{10}$$

$$U'_{baseLV} = U_{baseLV} + N_{TC_{pos2}} \left(\lfloor x_{p,2} \cdot 9 \rfloor + 1 \right) \frac{3\%}{100\%} U_{baseLV} \tag{11}$$

$$Z'_{baseLV} = \frac{\left(U'_{baseLV} \right)^2}{S_{base}} \tag{12}$$

3) **Št. Florjan 20/0.4 kV substation** *(voltage range of ±12%, 3% per tap step, nine tap positions)*

The modified LV network voltage and impedance base values are determined from (14) and (15), by considering the tap position $N_{TC_{pos3}}$ (13). The procedure is the same as for the Turiška vas substation, since the same OLTC type is considered in both MV/LV substations.

$$N_{TC_{pos3}} \in \boldsymbol{N}_{TC_{pos3}} = \{-4, -3, \cdots, 0, \cdots, 3, 4\} \tag{13}$$

$$U'_{baseLV} = U_{baseLV} + N_{TC_{pos3}} \left(\lfloor x_{p,2} \cdot 9 \rfloor + 1 \right) \frac{3\%}{100\%} U_{baseLV} \tag{14}$$

$$Z'_{baseLV} = \frac{\left(U'_{baseLV} \right)^2}{S_{base}} \tag{15}$$

3.2 *Load modeling*

The loads and generation units are defined by the consumed or generated complex power. However, the loading power values may depend on the node voltage at the load connection point. To describe this dependency, polynomial models of the active (16) and reactive power (17) of the load connected to the node (*i*) are used [10].

$$P_{load,i} = P_{load,i} \left(a_0 + a_1 \left| \underline{U}_i \right| + a_2 \left| \underline{U}_i \right|^2 \right) \tag{16}$$

$$Q_{load,i} = Q_{load,i} \left(r_0 + r_1 \left| \underline{U}_i \right| + r_2 \left| \underline{U}_i \right|^2 \right) \tag{17}$$

The constant power, constant current, and constant impedance loading models are defined using the coefficient pairs (a_0, r_0) (a_1, r_1) and (a_2, r_2) representing the load independence, linear dependence, and quadratic dependence on the voltage, respectively. Each coefficient defines the share of each model in the polynomial model, and the coefficients sum up to the value of 1 (18) and (19).

$$a_0 + a_1 + a_2 = 1 \tag{18}$$

$$r_0 + r_1 + r_2 = 1 \tag{19}$$

The extreme loading models are considered, i.e., a constant power (CPM) and a constant impedance loading model (CIM), to demonstrate the impact of the loads behavior on OLTC operation and network control.

3.3 Results

The optimal tap positions for each OLTC-equipped transformer are determined on an hourly basis of an average day in a month. The average loading and generation profiles are obtained from long-term measurements in multiple MV/LV substations in the network. An example of an average loading profiles for an average day in a month for the Turiška vas substation is given in Figure 5.

Figure 5 and Figure 6 show the optimal tap positions obtained for 288 hourly calculations for each hour of an average day in a month (12 months times 24 hours), for the network loads modeled as CPM and CIM. The possible values of tap positions for each substation are given in (9), (10), and (13). The network loads are assumed to be of an inductive nature.

The results in Figure 5 illustrate that the tap positions for CPM are increased to the highest limit value. With loading independent from the nodal voltage, the increased voltage profile result in lower power losses. It is also observed that the tap positions at the MV/LV substations need to be modified only twice a day, i.e., once in the morning and once in the evening, following the increase and the decrease in the network loading. The determined tap positions should not be exceeded as they would cause overvoltages in some parts of the network.

The tap-changer operation differs significantly when using CIM, representing the load quadratic voltage dependency (Figure 6). The tap position at the Turiška vas MV/LV substation is kept at the highest possible setting $(+4 \cdot 3\%)$ at any time, while the tap position at the Št. Florjan MV/LV substation lowers $(+3 \cdot 3\%)$ at an overvoltages occurrence. On the contrary, the HV/MV substation tap position is lowered down to the lowest possible value. The tap position fluctuates between the positions $6 \cdot 1.33\%$ and $0 \cdot 1.33\%$ following the loading profile curve (Figure 5). A lower tap position in a HV/MV substation ensures a lower voltage profile at the 20 kV level, resulting in a reduced power consumed by CIM loads. A reduced power consumption results in lower line currents hence, in lower network power losses.

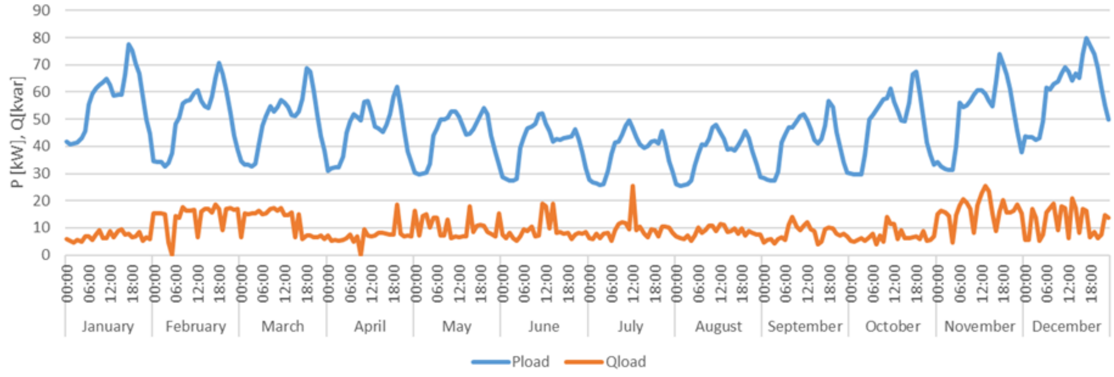

Figure 4. Hourly loading profile representing an average day in a month for Turiška vas substation.

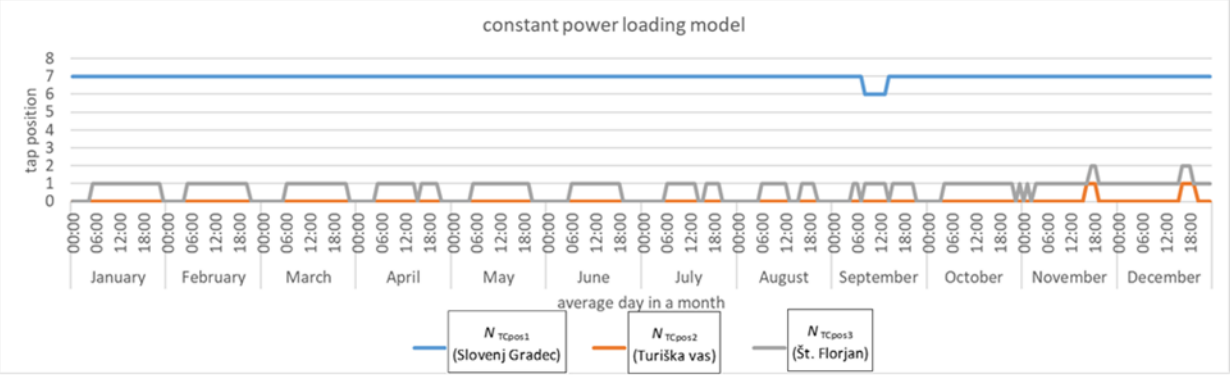

Figure 5. Optimal hourly tap positions of an average day in a month (CPM).

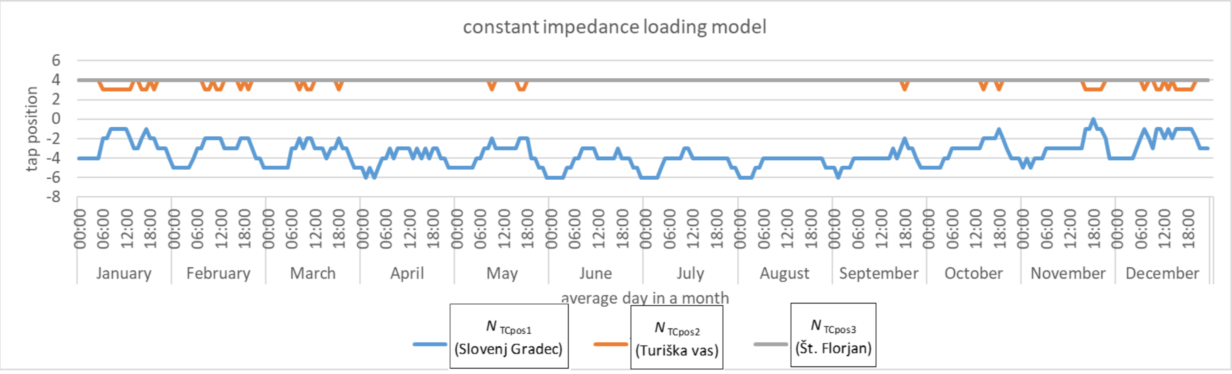

Figure 6: Optimal hourly tap positions of an average day in a month (CIM).

The presented results may be used to predict the annual number of tap operations for each OLTC. Application of an advanced voltage control mechanism and the algorithm, such as the one proposed in the paper, will result in a frequent change of OLTC tap position, thus potentially increasing its wear and tear. By multiplying the number of changes of tap positions per average day in a month (Figure 5 and Figure 6) with the number of the days in a month, the number of annual tap operations for each OLTC-equipped substation, can be predicted (Table 1).

Table 1. Prediction of the number of annual tap operations.

Constant power loading model (CPM)			**Constant impedance loading model (CIM)**		
Slovenj Gradec	Turiška vas	Št. Florjan	Slovenj Gradec	Turiška vas	Št. Florjan
60	122	1186	3312	1522	0

The average number of the daily tap operations in a day is in the range from 10 to 25, i.e., from 3650 to 9125 tap operations per year [11]. If the numbers given in Table 1 are three-times higher, the number of tap operations due to the presented optimization algorithm does not importantly affect the OLTC wear and tear, since the numbers are still smaller than in a usual OLTC operation. The OLTCs in the considered MV/LV substations are of a vacuum-type requiring no maintenance in their operational lifetime and the maximum predicted 1522 annual tap operations (based on hourly calculations) could not affect the OLTC wear and tear.

4 CONCLUSION

The paper proposes a DE-based algorithm to find the optimal tap positions of the OLTC-equipped transformers operating in the primary and the secondary voltage level. The algorithm keeps the voltages and currents within the limits set by the applicable standards and minimizes the network power losses. With the increase in the number of the OLTC-equipped transformers in modern power distribution networks, the number of the possible combinations of the OLTC tap positions increases too. Therefore, the solution to the problem of finding their optimal tap positions is using an optimization method instead of checking among all the possible combinations. DE is an optimization method implemented in the proposed algorithm, although other methods to solve an integer problem can also be used. The proposed DE-based algorithm to find the optimal tap positions gives an accurate result in an acceptable time frame (the average calculation time is less than 15 seconds). The DE algorithm is relatively easy to implement and modify to respond to a discrete nature of an investigated problem.

The optimal tap-operations behavior depends on the loading model used and requires a proper modeling of the power distribution network elements. Therefore, the load behavior as a function of the network voltage should be permanently monitored and evaluated during the network operation. This way, a proper loading model to determine the optimal tap positions, can be provided compliably with the actual network conditions.

The impact of the proposed algorithm on the increased number of tap operations and, consequently, on the OLTC wear and tear is not important, as the predicted number of the annual tap operations is significantly smaller than the average daily number of tap operations. However, in an actual network operation, the load and generation change continuously, without being seen in average hourly measured values. Thus, to give a relevant prediction of the required number of tap operations per year, the load and generation data should be provided with a greater time resolution. If simulations using other input data would predict a much higher number of the tap operations, a new objective function could be developed. Such function would incorporate the cost of a single tap operation based on a tap-changer price, cost of its maintenance, and operations lifetime and maintenance schedule.

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