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Optimal Control Actions for Managing High Voltage Occurrences in Operation

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SUMMARY

In transmission systems, the possibility of violating high voltage limit increases during light load periods. Nowadays, light loading conditions occur more often due to the integration of renewable energy resources (RES) in distribution systems. Moreover, the issue of violating high voltage limit could be more severe if RES connected to transmission systems are injecting more active power to the system. This paper proposes an optimization approach for controlling high voltage occurrences in transmission systems in operation. Control variables considered in the proposed optimization approach include switching shunt devices, switching transmission lines, changing tap position of transformer taps, active power curtailment from RES, active power redispatch from conventional generators, and adjusting voltage setpoint of regulated buses. Upon the occurrence of high voltage limit violation, available control variables within the area of interest would be considered in the optimization approach while control variables in neighbouring utilities would be fixed. Results from 2000-bus synthetic grid and from several EMS cases of actual system with high voltage limit violations are used to demonstrate the applicability and effectiveness of the proposed optimization approach.

KEYWORDS

Optimal power flow, power transmission control, transmission switching, voltage control, voltage violation

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1 INTRODUCTION

The occurrence of high voltage issues on the transmission system is increasing, mainly during low-load periods. Low-load periods occur more frequently due to integration of RES in distribution systems reducing the loading on transmission system. Increased penetration of RES in transmission system reduces the loading even further. At times, operators are exhausting traditional operational procedures to mitigate these issues and are employing more extreme measures like switching out facilities to try to maintain voltage below the defined normal high limit and active power curtailment from RES connected to transmission and distribution systems. Even though operators can properly implement these measures, there are instances where a detailed analysis is needed to avoid potential adverse impact on system operation security and to improve the efficacy of the mitigation measures.

EPRI conducted a comprehensive industry survey in 2019 to gain a deeper understanding of the high voltage problem [2], how it was affecting system operations, and to identify specific industry needs and potential solution strategies. According to the survey results, most transmission companies are experiencing some degree of increasing high voltage issues. Those surveyed identified various drivers behind high voltage operating issues with the most dominant being extra high voltage transmission system additions to meet reliability needs during peak load periods and retirement of existing generation resources with capability to absorb reactive power. Some entities associated high voltage instances with maintenance outages on the system and integration of RES, but to a lesser extent. Survey results indicated there is a general desire to look at new and improved tools to determine the potential for high voltage issues and provide recommendations of remedial actions. Also, guidance for maximum sustained high voltage operation limits are needed. Entities have been improving operator tools and processes to better deal with high voltage problems, but a gap exists in the area of recommending mitigation actions for operators. In most cases, operators currently implement control actions from experience rather than based on the outcome of dedicated analysis tools. Therefore, considering the trend toward increasing high voltage problems in operations, the need for improved procedures and suitable analysis tools has become apparent. The objective of this paper is to develop strategies, methods, and software tools to help operators evaluate and implement more efficient and safe control actions to mitigate high voltage problems in operations.

This paper presents the optimization tool developed to find the optimal control actions to alleviate high voltage issue in transmission systems. This tool is designed for operation purposes which impose several constraints. These constraints include using controls only within the system operator jurisdiction to alleviate high voltage issue. Limiting number of control actions is preferred to enable system operators handle these changes. Several EMS cases from different utilities with high voltage limit violations are used to demonstrate the applicability and effectiveness of the proposed optimization approach.

This paper is organized as follows: Section 3 reveiws voltage control in transmission systems. Section 4 introduces the optimization problem and section 5 presents the solution algorithm proposed in this paper. Section 6 shows the results and section 7 concludes the paper.

2 VOLTAGE CONTROL IN TRANSMISSION SYSTEMS

In transmission system, there are several control actions that could be used to control the voltage of the system. The following subsections discuss each control action commonly used by utilities.

2.1 Switching shunt devices

Switching shunt devices are typically used to adapt to slowly changing system conditions such as daily and seasonal load cycles and changes to scheduled transactions. Shunt capacitors are used to provide normal or intact-system voltage support. To increase their effectiveness, shunt capacitors are located near to reactive load. Shunt reactors are commonly used when the system is lightly loaded during night. They are usually needed to absorb or offset naturally occurring capacitance of transmission lines or underground cables during light load conditions [5].

2.2 Voltage set point of regulator buses

Regulated buses are the buses whose voltage magnitude is controlled by var resources e.g., synchronous condensers, synchronous generators, wind, and PV generation with reactive power capabilities, etc. Changing voltage setpoint of regulated buses effectively changes the voltage of the surrounding buses.

2.3 Transformer tap changers

The on-load tap changer of transformer can adjust the winding ratio in steps between the primary and the secondary sides and then varies the voltage at the load side.

2.4 Transmission line switching

During light loading conditions, reactive power from line charging might exceeds reactive power absorbed by the series reactance of the line. Transmission system operators switch lines in and out to relief voltage violation during light loading conditions. The Northeast Power Coordination Council includes switch out transmission lines in the list of possible actions to avoid abnormal voltage conditions [3].

2.5 Active power curtailment and generation redispatch

Active power curtailment and generation redispatch are considered the most expensive solution and the last resort for controlling the voltage within transmission systems. For RES connected to transmission system, active power curtailment reduces the amount of active power injected by RES, as the voltage at their buses increase above a certain value [6]. Generation redispatch of conventional synchronous generators changes power flow in the network and hence changes line loadings and system voltages [4].

3 OPTIMIZATION PROBLEM FORMULATION

In this section, a mathematical formulation of the optimization problem considered in the work is presented. The optimization problem is formulated as nonlinear program (NLP) problem:

$$minimize\ \alpha_1 \sum_{i\in N_e} (v_i - v_i^s)^2 + \alpha_2 \sum_{i\in N_i} (v_i - v_i^s)^2 + \alpha_3 \sum_{i\in N_h} (v_i - \hat{v}_i)^2 + \alpha_4 \sum_{i\in N_b} (b_i - b_i^0)^2 + \alpha_5 \sum_{km\in N_l} (z_{km} - z_{km}^0)^2 + \alpha_6 \sum_{km\in N_t} (\tau_{km} - \tau_{km}^0)^2 + \alpha_7 \sum_{i\in N_g} (P_i^g - P_i^0)^2 \quad (1)$$

$$subject\ \ to\ P_k^g - P_k^l - \sum_{m\in[n]} z_{km} v_k v_m (G_{km}\cos\theta_{km} + B_{km}\sin\theta_{km}) = 0, \quad \forall k \in [n], \quad (2)$$

$$Q_k^g - Q_k^l + B_{kk} v_k^2 - (1 - z_{km}) b_k^{sh} v_k^2 - \sum_{m\in[n], m\neq k} z_{km} v_k v_m (G_{km}\sin\theta_{km} - B_{km}\cos\theta_{km}) = 0,\ \forall k \in [n], \quad (3)$$

$$\underline{Q}_k \leq Q_k^g \leq \overline{Q}_k,\ \forall k \in [n], \tag{4}$$
$$\underline{P}_k \leq P_k^g \leq \overline{P}_k,\ \forall k \in [n], \tag{5}$$
$$\underline{v}_k \leq v_k \leq \overline{v}_k,\ \forall k \in [n], \tag{6}$$
$$\underline{b}_k \leq b_k \leq \overline{b}_k,\ \forall k \in [n], \tag{7}$$
$$\underline{\tau}_{km} \leq \tau_{km} \leq \overline{\tau}_{km},\ \forall (k,m) \in [n], \tag{8}$$
$$\textstyle\sum_{i\in N_l} (1 - z_{km}) \leq Ns, \tag{9}$$

where α_i is the weight parameter and $\alpha_1 \gg \alpha_i\ \forall i > 1$, N_e is set of voltage regulated buses in external network i.e. neighboring utilities, v_i is the voltage magnitude of bus i, v_i^s is the voltage setpoint of the regulated bus i, N_i is the set of voltage regulated buses in the internal network, N_h is the set of buses with high voltage limit violation, $\hat{v}_i$ is the mid-point of voltage limit of bus i, N_b is the set of shunt devices, b_i^0 is the initial value of the shunt device i, N_l is set of lines considered for switching, z_{km} is the binary variable representing the status of the line i between bus k and bus m, z_{km}^0 is initial status of the line km, $z_{km}^0 = 1$ if line is initially in service and $z_{km}^0 = 0$ otherwise, N_t is the set of transformer taps τ_i or τ_{km} is the tap ratio of transformer i between bus k and m, N_g is the set of generators considered for rescheduling or for curtailment, P_i^g, Q_i^g are the active and reactive power from generator at bus i, respectively, P_i^l, Q_i^l are the active and reactive power of load at bus i, respectively, n is the set of in service buses in the system, b_k^{sh} is the line charging at bus k, G_{km}, B_{km} are elements of the conductance and susceptance matrix, $\underline{Q}_k, \overline{Q}_k, \underline{b}_k, \overline{b}_k, \underline{P}_k, \overline{P}_k, \underline{\tau}_k, \overline{\tau}_k \in \mathbb{R}$, $\underline{v}_k, \overline{v}_k \in \mathbb{R}_{++}$, and N_s is the maximum number of switched-out lines.

The objective function 1 consists of a summation of different penalty terms with different weights. Control variables, i.e. shunt devices, transformer taps, and voltage setpoint of the regulated buses in the neighboring utilities should be fixed as the system operator can only control devices within their jurisdiction. Penalty function for regulated buses in the external network with very high weight is included to limit the deviation of the voltage setpoints in the external network from their initial values. There is a penalty function for buses whose voltage magnitude violates their upper limit. the rest of the penalty function terms are used to limit the number of control actions required by the system operator to eliminate voltage violations. The weight for each penalty function determines the priority of changing control variables e.g., if $\alpha_5 > \alpha_6$ then changing tap changer is less costly than switching lines.

The constraints includes power balance equations 2 and 3, bounds of generator reactive powers 4, bounds of generator active powers 5, bounds of voltage magnitude 6, bounds of transformer taps 8, bounds of shunt susceptance 7, and finally constraint 9 to limit number of lines to be switched out.

4 SOLUTION ALGORITHM

The optimization problem 4 has some discrete variables such as line switching binary variables z, shunt devices variables, and transformer taps. Solving this problem with mixed-integer nonlinear solver (MINLP) would be computationally expensive. Moreover, the objective function is not directly associated with economic cost, but instead with penalty terms that encourage solution properties that lead to robust and secure operating setpoints in practice. Therefore, local optimal solution would be enough and relaxing discrete variables to continuous variables and use NLP solver to solve the optimization problem and then round discrete variables.

Algorithm 1: Proposed Solution Algorithm

```
Get network (From EMS)
Define area of interest as AREA
Find control variables within the area of interest
FIXED_VARS = [ ]
Iter = 0
while size(FIXED_VARS) < number of discrete variables OR MAX_ITERATION do
    Construct optimization problem while fixing variables in FIXED_VARS
    Solve constructed optimization problem by NLP solver
    Fix discrete variables that are close to their integer values and add to FIXED_VARS
    Update Penalty parameters and setpoints for discrete variables
    Iter += 1
end while
Round discrete variables
Return control variables
```

To avoid getting infeasible solution due to rounding discrete variables, this paper proposes to solve this optimization problem in iterative manner as described in 5. The first step is to find buses with voltage violation and control variables that are within the area of interest. As mentioned above, shunt devices, transformer taps, and voltage setpoints in the external network would be fixed for the external network. The next step would be solving the optimization problem iteratively using NLP solver e.g., the open source solver IPOPT [7]) is used in this paper. At each iteration, discrete variables that are close to their integer values are rounded and fixed. Other discrete variables whose values are between two integer values, the parameters in the objective function that represent their initial point i.e., b_i^0 for shunt devices, z_{km}^0 for lines, and τ_{km}^0 for transformer taps, would be updated to the rounded value of the discrete variables. In addition, the penalty parameters for penalty terms of the discrete variables in the objective function i.e., α_4, α_5, and α_6, increase at each iteration. This process encourages discrete variables to move closer to a valid integer value. This iterative process stops when all discrete variables are fixed to a correct integer value or the maximum number of iterations is reached.

5 RESULTS AND DISCUSSION

5.1 2000-bus synthetic grid results

In this section, 2000-bus synthetic grid [1] is used to test the optimization algorithm proposed in this paper. Voltage profile of the system is within limits. By removing shunt devices at bus 2096 and fixed shunt at bus 2017, several buses will have voltage higher than the upper limit of the voltage i.e., 1.05 pu in this paper. In the following case studies, the whole network will be considered in the optimization.

5.1.1 Case study 1

In this case study, only shunt devices are allowed to control the voltage. Transformer taps ratio, generators active power, system topology will not be considered in the optimization. The weight α_2 for adjusting voltage setpoints of regulated buses is set to high value to fix the voltage setpoints of the regulated buses. The optimization results show that shunt devices at bus 8138, 6221, 6151, 4131, and 2009 should be switched off to bring system voltage back the normal range between 0.95 and 1.05 pu. Voltage distribution for buses with base voltage 115.0 kV and higher is depicted in Figure 1 before (pre-OPT) and after (post-OPT) applying the control actions suggested by the optimization algorithm.

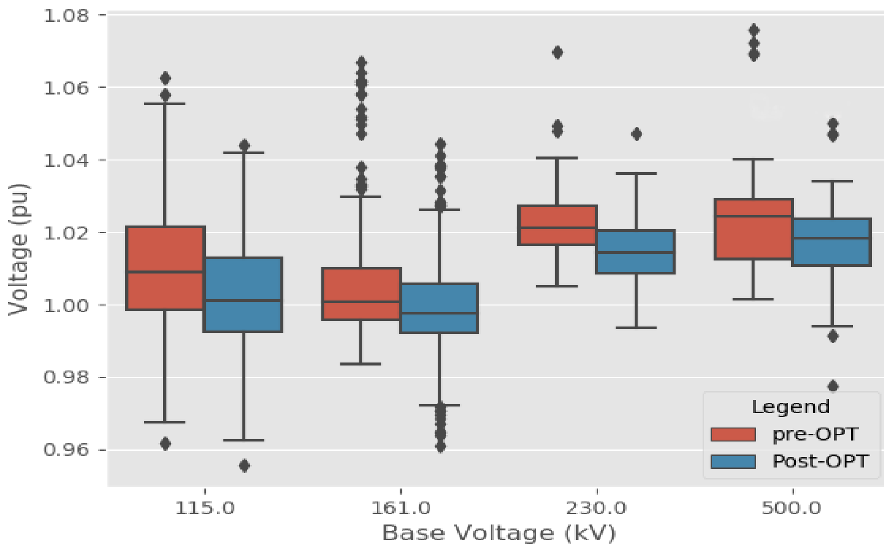

Figure 1: Voltage distribution - case study 1

5.1.2 Case study 2

In this case study, system topology changes are considered in the optimization algorithm to allow switching of transmission lines in addition to shunt devices to alleviate high voltage issue. In this case, the optimization algorithm suggested to switch off two capacitor banks at bus 6221 and 6151, in addition to switching off two transmission lines, the first line from bus 2017 to bus 2096 and from bus 4195 to bus 6239. Voltage distribution of the system buses is shown in Figure 2 where the voltage of all buses are within limits. Comparing voltage distribution in Figure 1 and 2, the voltage distribution for case study 2 is more tighter as in this case more control variables are allowed to control the voltage.

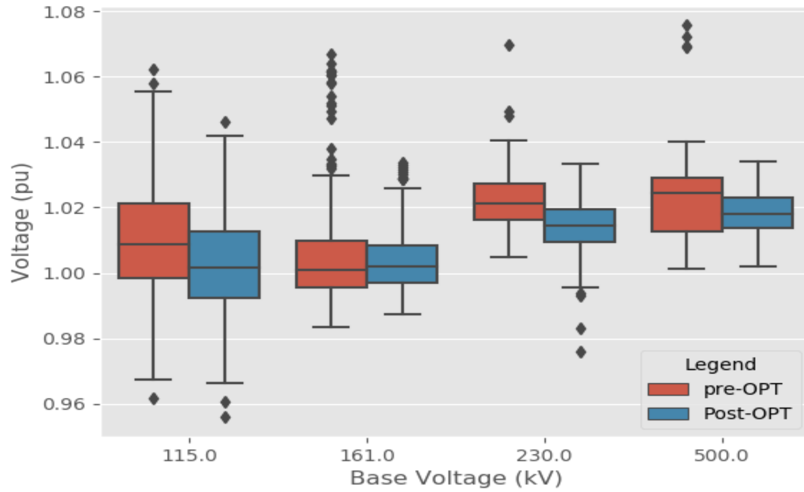

Figure 2: Voltage distribution - case study 2

5.2 Results from EMS case

In this section, analysis of different EMS case provided by utility in the Eastern Interconnection is presented. These EMS cases have high voltage limit violations due to some contingencies in the system. Table 1 presents number of buses with high voltage limit violations for buses with different base voltage. Table 2 shows number of control variables within the utility transmission system. This table ignore shunt devices and transformer taps within distribution systems.

Table 1: Summary of Voltage Violation

Base Voltage (kV)	High Voltage limit (pu)	Number of Buses with Voltage Violations
115.0	1.052 (121 kV)	27
230.0	1.045 (240 kV)	5
345.0	1.05 (362 kV)	3

Table 2: Control variables available within the utility Transmission System

Control Variable	Number of control variable
Shunt Devices	39
Transformer Taps	17
Regulated Buses	24
Lines (considered for Switching)	21
Wind Generators	16
Conventional Generators	13

The optimization model and solution algorithm proposed in this paper are used to find the optimal control actions required to alleviate high voltage limit violations in the system. Number of control actions should be manageable so system operators could handle the required actions. Table 3 summarizes the control actions required to alleviate high voltage violation issue in the system. From this table, voltage setpoints of three voltage regulated buses should be updated, three shunt devices (two capacitor banks and one reactor bank) should be switched off, one transformer tap needs to be adjusted, and three lines should be switched off.

Table 3: Control Actions required to alleviate high voltage limit violations

Control Variable	Number of control actions required
Shunt Devices	3
Transformer Taps	1
Regulated Buses	3
Lines (considered for Switching)	3
Wind Generators	None
Conventional Generators	None

Figure 3 depicts voltage distribution of the system buses for the EMS case (with the label prt-OPT) and for the system after applying the control actions proposed by the optimization model (with the label post-OPT). With the proposed control actions, all buses have voltage within specified limits.

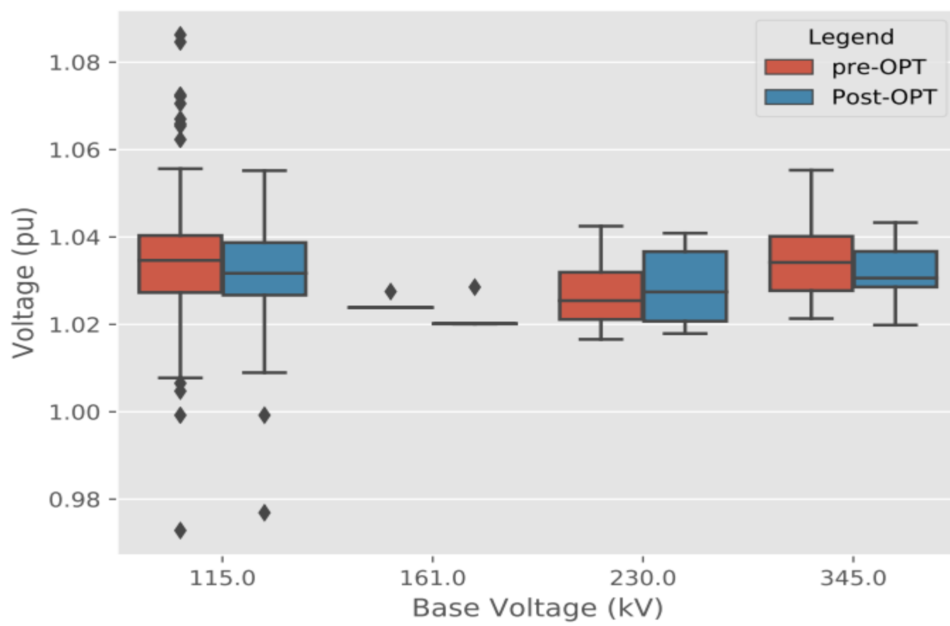

Figure 3: Voltage distribution

Figure 4 shows reactive power from generators for the EMS case (pre-OPT) and after applying the proposed control actions from the optimization model (post-OPT). Reactive power from generators is reduced which gives the new control actions extra credits as the system now has more dynamic var reserve.

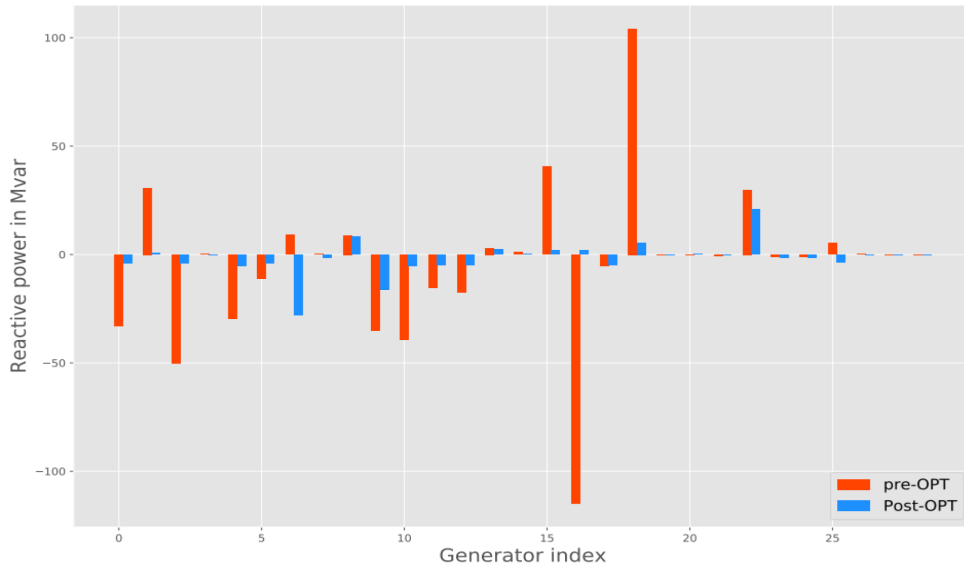

Figure 4: Generator reactive powers

Table 4 presents the total system losses and total line charging before and after applying the control actions. Line charging is reduced which is reasonable after removing three lines. System losses is also slightly reduced.

Table 4: System Losses and Line charging

	System Losses (MW)	Line Charging (Mvar)
Pre-OPT	46.8	1008.6
Post-OPT	46.5	973.7

6 Conclusion

This paper proposes an optimization methodology and solution algorithm for controlling high voltage issues in transmission systems during operation. Several controls are considered in the optimization approach including shunt devices, line switching, transformer taps, active power curtailment from RES and active power redispatch. The optimization algorithm finds a few control actions that would be required to alleviate high voltage issue. The solution algorithm is suitable for large scale network and the results of real power system is presented.

BIBLIOGRAPHY

[1] Adam B. Birchfield, Ti Xu, Kathleen M. Gegner, Komal S. Shetye, and Thomas J. Overbye. Grid structural characteristics as validation criteria for synthetic networks. *IEEE Transactions on Power Systems*, 32(4):3258–3265, 2017.

[2] EPRI. Managing volt/var control issues challenges: Assessment of high voltage conditions in transmission system operation. Technical report, Dec. 2019.

[3] Emily B. Fisher, Richard P. O'Neill, and Michael C. Ferris. Optimal transmission switching. *IEEE Transactions on Power Systems*, 23(3):1346–1355, 2008.

[4] Abbas Rabiee, Alireza Soroudi, Behnam Mohammadi-ivatloo, and Mostafa Parniani. Corrective voltage control scheme considering demand response and stochastic wind power. *IEEE Transactions on Power Systems*, 29(6):2965–2973, 2014.

[5] TIS Reactive Support and Control Subteam. Reactive support and control whitepaper. Technical report, Sep 2009.

[6] Reinaldo Tonkoski and Luiz A.C. Lopes. Impact of active power curtailment on overvoltage prevention and energy production of pv inverters connected to low voltage residential feeders. *Renewable Energy*, 36(12):3566–3574, 2011.

[7] Andreas Wachter. *An interior point algorithm for large-scale nonlinear optimization with applications in process engineering*. PhD thesis, Carnegie Mellon University, 2002.