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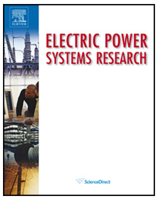

# Optimal OLTC voltage control scheme to enable high solar penetrations

Changfu Li[a,*], Vahid R. Disfani[a,b], Zachary K. Pecenak[a], Saeed Mohajeryami[a], Jan Kleissl[a]

[a] Center for Energy Research and the Department of Mechanical and Aerospace Engineering at the University of California San Diego, La Jolla, CA 92093, USA
[b] Department of Electrical Engineering at the University of Tennessee at Chattanooga, Chattanooga, TN 37403, USA

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ABSTRACT

High solar Photovoltaic (PV) penetration on distribution systems can cause over-voltage problems. To this end, an Optimal Tap Control (OTC) method is proposed to regulate On-Load Tap Changers (OLTCs) by minimizing the maximum deviation of the voltage profile from 1 p.u. on the entire feeder. A secondary objective is to reduce the number of tap operations (TOs), which is implemented for the optimization horizon based on voltage forecasts derived from high resolution PV generation forecasts. A linearization technique is applied to make the optimization problem convex and able to be solved at operational timescales. Simulations on a PC show the solution time for one time step is only 1.1 s for a large feeder with 4 OLTCs and 1623 buses. OTC results are compared against existing methods through simulations on two feeders in the Californian network. OTC is firstly compared against an advanced rule-based Voltage Level Control (VLC) method. OTC and VLC achieve the same reduction of voltage violations, but unlike VLC, OTC is capable of coordinating multiple OLTCs. Scalability to multiple OLTCs is therefore demonstrated against a basic conventional rule-based control method called Autonomous Tap Control (ATC). Comparing to ATC, the test feeder under control of OTC can accommodate around 67% more PV without over-voltage issues. Though a side effect of OTC is an increase in tap operations, the secondary objective functionally balances operations between all OLTCs such that impacts on their lifetime and maintenance are minimized.

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## 1. Introduction

The amount of variable distributed generation (VDG) such as solar PV being connected to the grid continues to increase each year as a result of their many technical, economic, and environmental benefits [1]. However, existing distribution networks may not be capable of handling large amounts of VDG since they are initially designed assuming centralized off-site generation.

Variability and intermittency of VDGs, in particular, present significant challenges to voltage regulation in distribution systems [2]. Traditionally, to address the voltage issues on the distribution system, OLTCs and voltage regulators are typically employed to maintain the voltage on the secondary side of power transformers within regulatory limits.

Conventional ATC of OLTC maintains a fixed voltage at the transformer's secondary side based on measured local busbar voltage, a line-drop compensator, or remote voltage measurements [3]. As OLTCs are typically configured assuming a voltage drop along the feeder, a voltage rise caused by reverse power flow during periods with low demand and high solar power feed-in can lead to over-voltages [4]. Moreover, with high PV penetration on a distribution system, high frequency solar ramping caused by fast-moving clouds can result in excessive TOs [5].

In order to solve voltage problems resulting from high penetration of VDG on distribution systems, various advanced control methods have been proposed. Several researchers applied rule-based control of OLTCs by replacing local busbar voltage with voltage measurements or estimates from feeder end points and/or critical nodes as the control signal [6–8,3]. However, in these works, the voltage measurements/estimates are only used to control tap position of substation OLTC and coordination between multiple OLTCs is not studied. Therefore, these methods suffer from lack of scalability and are not applicable to feeders with multiple OLTCs.

Other researchers exploited the capability of devices other than OLTCs. A DSTATCOM was used in [9] to damp impacts of residential PV power fluctuations on the OLTC operation. However, the study is done on a small balanced network and no coordination is considered between DSTATCOM and OLTCs. Coordination between energy

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[*] Corresponding author.

*E-mail addresses:* chl447@ucsd.edu (C. Li), vahid-disfani@utc.edu (V.R. Disfani), zpecenak@ucsd.edu (Z.K. Pecenak), samohajeryami@ucsd.edu (S. Mohajeryami), jkleissl@ucsd.edu (J. Kleissl).

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**Nomenclature**

| | |
|---|---|
| $\tau$ | tap position |
| $a$ | tap ratio |
| $J$ | objective function |
| $P$ | set of all OLTCs |
| $p$ | index of OLTC |
| $T$ | set of all time steps |
| $t$ | index of time step |
| $w_1$ | weighting factor of voltage deviation objective $J_1$ |
| $w_2$ | weighting factor of tap operation objective $J_2$ |
| $Y$ | admittance matrix |
| $Z$ | impedance matrix |
| ATC | Autonomous Tap Control |
| DSO | distribution system operator |
| DSTATCOM | distribution static compensator |
| OLTC | On-Load Tap Changer |
| OTC | Optimal Tap Control |
| PV | photovoltaic |
| SC | shunt capacitor |
| ShR | shunt reactor |
| SVC | static var compensator |
| TO | tap operation |
| VAr | volt-ampere reactive |
| VDG | variable distributed generation |
| VLC | Voltage Level Control |

storage systems and OLTC is studied in [10] for peak load shaving, power loss reduction, and tap changer stress relief (reduction in TO and reducing operations close to tap limits). However, the proposed solution requires adoption of costly battery storage systems and does not consider coordination of multiple OLTCs. The authors in [11] have studied voltage control by using faster static var compensator (SVC) and slower-responding OLTC to limit SVC reactive power output and reset voltage reference after disturbances for effective voltage support. However, the control is only based on local voltage measurements and as a result the SVC and OLTC are not truly coordinated in an optimal way. Moreover, only one OLTC is used in this work, which makes the scalability of the proposed approach questionable.

A central control methodology can achieve coordinated control of different voltage regulation devices and optimize their operations over a time horizon by taking advantage of load and solar forecast. In [12], OLTCs, shunt capacitors (SCs), shunt reactors (ShRs), and SVC are optimally dispatched hourly to minimize voltage deviation and energy losses. Similarly, reference [13] updates optimal tap position of OLTC and reactive power output of PV inverters every 50 s to minimize voltage deviation. Simulation results in both studies show that the proposed methods are able to achieve the desired objectives. However in both works, a genetic algorithm is used to search for the optimal solution, which can be time-consuming considering the extensive search space for the coordinated control of different devices.

Reference [14] presents a two-stage approach for solving the optimal voltage regulation problem with coordination between OLTC and SVC. The optimization problem is solved hourly to minimize power losses and TO based on one hour ahead forecasts. The two-stage method is also adopted to solve the coordination problem of more devices including OLTC, SC, and SVC under load and distributed generation uncertainty in [15]. Although the proposed method already improves the solution time by a large margin comparing to existing methods, it still takes around 25 s to solve the problem for one time step on the small IEEE 123-bus system in [14] and the solution time increases to 58 s in [15] which has more devices on the same test feeder. Since PV variability in partly cloudy conditions over a distribution system typically occurs on the order of a few minutes, an hourly time step is insufficient. Rather sub-minute time steps are recommended and therefore this two-stage approach is still questionable for high-resolution application for real distribution feeders, which usually contain thousands of buses. Reference [16] proposes and successfully demonstrates a coordinated reactive power control of PV to minimize TO and avoid operating the OLTC at its control limits. However, only coordination of PV and substation OLTC is considered, while the two other OLTCs operates autonomously.

Despite showing promising results, all of the optimal control methods in [12–16] are tested on simple distribution networks with only a few or evenly-distributed PV systems. In terms of PV generation profiles, only reference [13] adopts the required sub-minute generation profile during partly cloudy conditions while low-resolution (1 h) generation profiles for a clear-sky day are used in [12,14,15]. Reference [16] applies PV profiles with 30 s resolution but it is also for clear day without solar ramps. Moreover, the same generation profile is used for all PVs in these studies even though it is very critical to use unique and realistic generation profiles for each PV, and the importance of applying realistic individual PV generation profiles has been demonstrated in [17].

In addition, TO step limits between two consecutive simulation time steps have not been considered which could lead to unrealistic operating decisions of OLTC. For example, reference [14] provides an additional test case to show the proposed method's ability of dealing with fast-moving clouds effects, however, the results shows that one OLTC would need to switch by eight steps in less than 1 min, which is a challenging and arguably impractical task for conventional OLTC with slow mechanical switching gear and the typical 30 to 60 s time delay [18].

In summary, application of existing optimal control methods to sub-minute high-resolution applications are questionable. Potential issues include large computation time, lack of consideration of realistic OLTC switch limits, limited testing on large real distribution feeder and realistic representation of distributed PV characteristics like random deployments and fast ramping events. To tackle these issues, we propose a multi-horizon, central optimization of OLTC tap position to minimize voltage deviation maxima throughout the feeder and minimize the number of TOs. High temporal and spatial resolution PV forecasts are employed to reflect a realistic picture of a feeder with high penetration of distributed VDGs.

The contributions of this paper to improve the state-of-the-art in optimal voltage control are:

(1) A novel linearization technique to represent the OLTC tap position and feeder voltage as a convex optimization problem which is solvable in an operational time scale at high-resolution (30 s).
(2) Coordination between multiple OLTCs.
(3) A flexible optimization platform that can be easily expanded to consider other optimization objectives and coordinated control of other devices including SCs and ShRs.
(4) Demonstration of the method in realistic conditions on real feeders.
(5) Using realistic OLTC switching limits.

The proposed method is firstly benchmarked against an advanced rule-based control method that is found in the literature and proven to be effective through simulations and field deployments. Since the rule-based control method does not coordinate multiple OLTCs, the proposed method is further compared against a conventional autonomous control method. These studies are carried out through simulations on two disparate California distribution feeders.

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