

COMPARATIVE STUDY OF TAP CHANGER CONTROL ALGORITHMS FOR DISTRIBUTION NETWORKS WITH HIGH PENETRATION OF RENEWABLES

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ABSTRACT

This paper reviews commonly implemented tap changer control algorithms and evaluates their effectiveness in networks with high penetration of renewable generation.

INTRODUCTION

The increasing share of intermittent renewable generation in the distribution network leads to frequent voltage fluctuations and over-voltages. Various solutions for voltage regulation in the distribution grid, such as grid extension, storage, reactive power control, on-load tap changing transformers, and voltage regulators on feeders, have been discussed. There is growing interest by utilities in the latter two options, which, however, require adequate control algorithms for their on-load tap changers (OLTCs).

Especially with regard to the growing number of renewables in the distribution grids, the requirements such OLTC controllers need to fulfill become more stringent. The increased voltage variability due to renewable generation may result in a high number of tap changes. In order to avoid accelerated wear-and-tear of the OLTC devices and thus maximize their lifetime, the number of tap operations should be limited to a minimum. Since a tap change always involves a step change in the voltage, unnecessary tap changes should be prevented, therefore ensuring a smooth voltage profile. Evidently, a further requirement of an OLTC controller is to keep the voltage inside the permissible limits. However, there is always a trade-off between these two objectives of curtailing the number of tap changes and minimizing the percentage of time outside the permissible voltage bandwidth.

BASIC PRINCIPLES OF OLTC CONTROL

The most important parameters of basic OLTC control are the voltage set point (V_{set}), the bandwidth (BW), and the time delay (t_{delay}) [2], [5].

Voltage Set Point and Bandwidth

The measured voltage (V_{meas}) at the OLTC is compared to a previously specified set-point voltage (V_{set}). The voltage controller acts on the difference

$$\Delta V = V_{meas} - V_{set}.$$

The voltage step nature of LTC output requires a dead band with a certain bandwidth. The voltage change per OLTC step (ΔV_{tap}) defines the minimum acceptable bandwidth as follows

$$BW > 2 \Delta V_{tap}.$$

As long as the measured voltage lies within this band, or

$$\Delta V \leq BW/2,$$

no tap change is triggered.

Time Delay

An intentional time delay (t_{delay}) is always included in the algorithm to avoid tap changer operations when the voltage excursion outside of the bandwidth is only of short duration. Once the measured voltage leaves the allowed dead band, the tap timer is started. As can be seen from Figure 1, no tap changing takes place if the voltage reenters the bandwidth before completely timing out (voltage profile B). Otherwise a tap change is triggered at the completion of the established time delay period which causes a step change in the voltage and brings the voltage level in-band (voltage profile A).

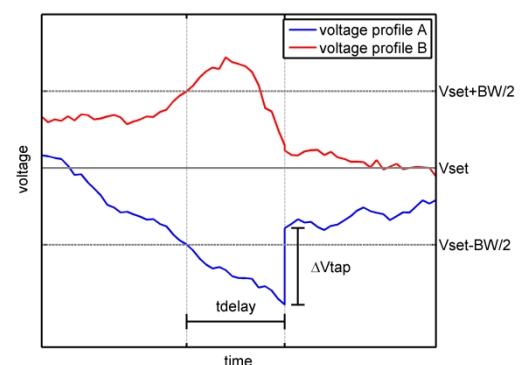


Figure 1: Illustration of basic OLTC control

The time delay can have values of tens of seconds to even a few minutes.

OLTC CONTROL ALGORITHMS

In order to obtain a comprehensive overview of existing OLTC control features, we have performed a thorough analysis of OLTC manufacturers and the control options they offer. Tap changer control includes many different aspects, such as timing options, voltage limit control, line drop compensation, operation under reverse power

flow, etc. [6]. Timing options refer to

- **Calculation of the time delay**
- **Reset of the tap timer upon reentering bandwidth**
- Multiple tap change sequences (if the voltage is still out of band after a successful tap change).

The options indicated in bold above will be addressed in this paper.

Calculation of Time Delay

Simple OLTC control algorithms use **definite** time delays, i.e., in case of a band violation, action is always taken after the same time delay period. In other types of control algorithms the time delay is variable: The further the voltage from a band edge, the smaller the time delay. As a consequence, large voltage deviations are rectified faster.

The **inverse** timer [3] uses

$$t_{var} = t_{delay} \frac{BW}{2|V_{meas} - V_{set}|},$$

the **linear** timer [1] uses

$$t_{var} = t_{delay} \left(1 - 0.1 \min\left(10, \frac{2|V_{meas} - V_{set}|}{BW}\right) \right),$$

and the **definite2** [1] timer uses

$$t_{var} = \begin{cases} t_{delay}, & |V_{meas} - V_{set}| < BW \\ t_{delay2}, & |V_{meas} - V_{set}| \geq BW \end{cases}$$

where $t_{delay2} < t_{delay}$.

If these types of time delay are used, the controller needs to continuously evaluate the tap timer integral I_{tap} . If the voltage lies within the allowed range, I_{tap} is equal to zero. When the voltage goes out of band, the controller starts accumulating the discrete tap timer integral according to

$$I_{tap} = I_{tap} + \frac{\Delta t}{t_{var}}$$

where Δt is the time resolution of the voltage measurement. A tap change is triggered for

$$I_{tap} \geq 1.$$

Reset Options

Typically, the tap timer is **instantaneously reset** to zero if the voltage reenters the bandwidth before completely timing out. Some controller manufacturers, however, offer additional reset options (cf. Figure 2).

The **integrating reset** timer reverses the countdown upon reentering bandwidth. The **delay reset** and **delay freeze reset** timers require an additional control parameter t_{reset} (settable delay in Figure 2). This parameter should not be confused with the main time delay of the tap timer (t_{delay}). The delay reset timer does not interrupt timing if the in-band voltage excursion is less than this settable delay (t_{reset}). The

delay freeze reset timer temporarily “freezes” timing for a time period of up to t_{reset} [7].

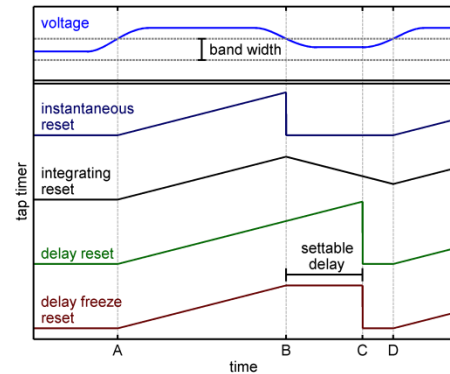


Figure 2: Reset options for tap timer [7]

SIMULATIONS

The OLTC control strategies have been compared by means of distribution system simulation.

Test Feeder

All simulations have been performed on a simple test feeder (cf. Figure 3) that has been adapted from [4].

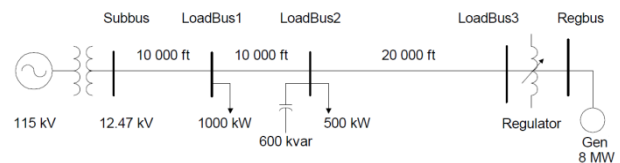


Figure 3: Test feeder with distributed generation unit (PV)

A large distributed PV plant is located at the end of the feeder. The regulator regulates the voltage at the Regbus to 122 V (in terms of a controller base voltage of 120 V) with a bandwidth of 3 V.

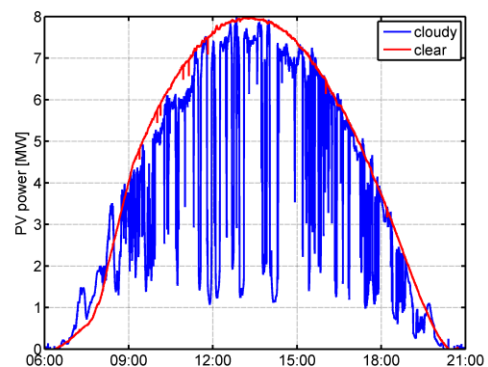


Figure 4: PV profiles for a clear and a cloudy day

Two measured PV profiles of a cloudy and a clear day have been used as generation profiles for the PV plant (cf. Figure 4).

The resulting voltage at the Regbus and the tap positions of the regulator are shown in Figure 5 and

Figure 6 for a definite time delay (t_{delay}) of 10 s with instantaneous reset timer.

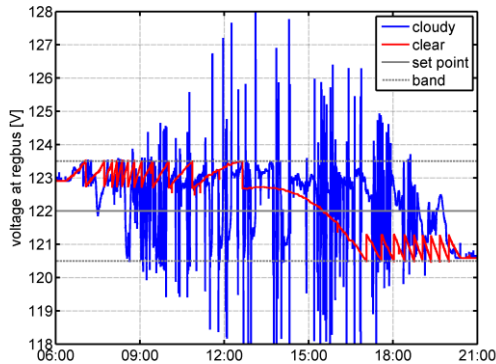


Figure 5: Voltage at Regbus (controller base voltage of 120V) for a definite time delay of 10 s with instantaneous reset timer

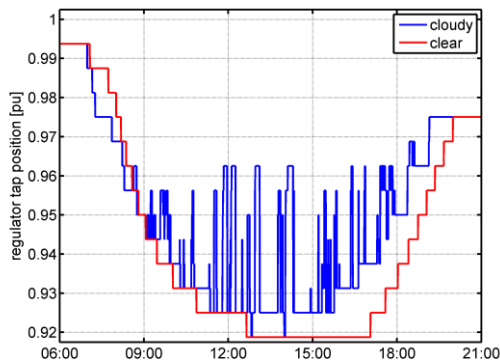


Figure 6: Tap position of the regulator for a definite time delay of 10 s with instantaneous reset timer

Evaluation Method

The purpose of the OLTC controller is to keep the voltage within the voltage band with a minimum number of tap changes. Therefore its performance can be measured using the following metrics

- number of tap changes
- percentage of time outside bandwidth
- average voltage deviation

$$\sum_{|V_{meas}(n) - V_{set}| > BW/2} \frac{|V_{meas}(n) - V_{set}(n)| - \frac{BW}{2}}{\# \text{ of points outside } BW}$$

Ideally, all these quantities should be kept to a minimum. However, usually there is a trade-off between minimum number of tap changes and compliance with the permissible voltage band.

RESULTS

Variation of Time Delay

In a first step a simple control algorithm using a definite time delay (t_{delay}) with instantaneous reset timer has

been studied. The time delay has been varied between 7 s and 90 s. Figure 7 and Figure 8 show the results for the cloudy and the clear day from Figure 4. Each point in the plots belongs to a load flow calculation over one day. The corresponding value of t_{delay} is given by the color code and by the black label.

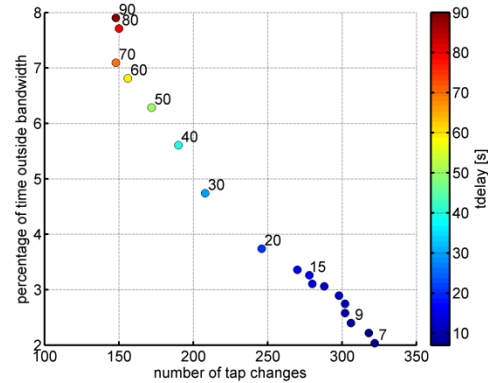


Figure 7: Number of tap changes and percentage of time outside bandwidth for an instantaneous resetting definite timer for varying time delays (t_{delay}) using the PV profile of a cloudy day.

On a cloudy day there is a trade-off between minimum number of tap changes and minimum voltage violation. Regulation requirements and the wear behavior of the on-load tap changing transformer determine the appropriate setting for the time delay (t_{delay}). When choosing $t_{delay} = 10$ s in this example, the percentage of time outside bandwidth is smaller than 3%, but 300 tap changes per day are needed. The number of tap changes can be halved for $t_{delay} = 70$ s at the expense of a longer time period outside the permissible bandwidth (7%).

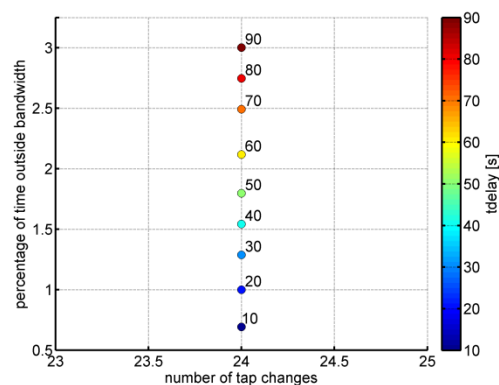


Figure 8: Number of tap changes and percentage of time outside bandwidth for an instantaneous resetting definite timer and varying time delays (t_{delay}) using the PV profile of a clear day

The situation is different on a clear day. The number of tap changes cannot be reduced and small time delays (e.g. $t_{delay} = 10$ s) lead to minimum voltage violations.

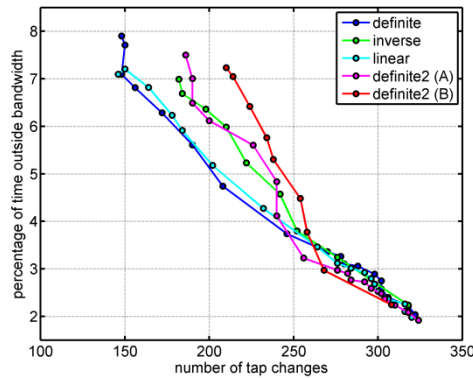


Figure 9: Number of tap changes and percentage of time outside bandwidth for different types of time delay (definite, inverse, linear, definite2) using the “cloudy” PV profile

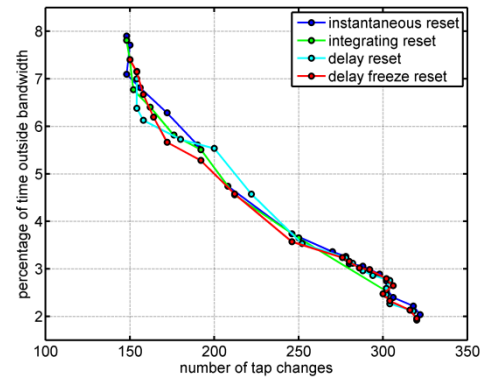


Figure 11: Number of tap changes and percentage of time outside bandwidth for different reset options (instantaneous, integrating, delay, delay freeze) using the “cloudy” PV profile

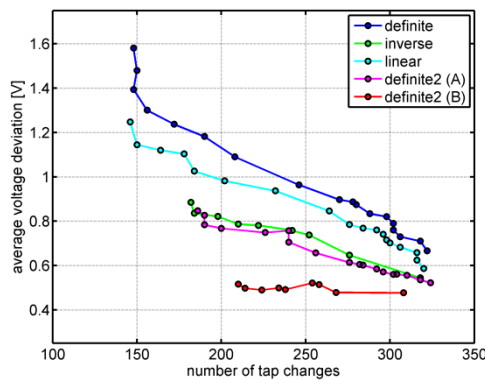


Figure 10: Number of tap changes and average voltage deviation for different types of time delay (definite, inverse, linear, definite2) using the “cloudy” PV profile

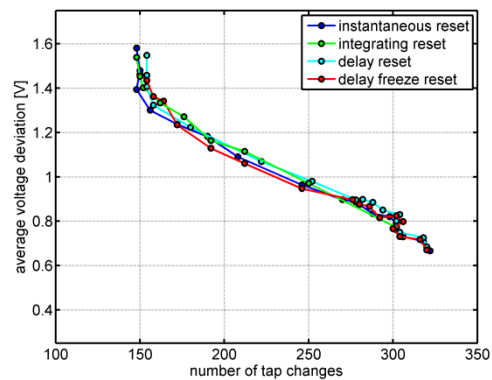


Figure 12: Number of tap changes and average voltage deviation for different reset options (instantaneous, integrating, delay, delay freeze) using the “cloudy” PV profile

Comparison of Control Algorithms

The performance of different control strategies can be evaluated by comparing the respective trade-off curves between number of tap changes and voltage violation. In Figure 9 and Figure 10 these trade-off curves are shown for various types of time delays (definite, inverse, linear, definite2). Figure 11 and Figure 12 compare different reset options (instantaneous reset, integrating reset, delay reset, delay freeze reset).

The blue curves in Figure 9 and Figure 11 contain the same data as Figure 7. Each point represents a load flow simulation over one day using an instantaneous resetting definite timer with a certain time delay (t_{delay}). The time delay has been varied between 7 s and 90 s. For better clarity the labels for t_{delay} have been omitted.

All curves in Figure 9 and Figure 10 use the instantaneous reset option. The definite2 timer has been considered twice with two different settings for t_{delay2} . Case (A) uses $t_{delay2} = 0.3 t_{delay}$, whereas case (B) uses $t_{delay2} = 0.05 t_{delay}$. The inverse, linear and definite2 timers rectify large voltage violations faster than a simple definite timer. Accordingly, the voltage

deviations are largest for the definite timer (cf. Figure 10). Minimal voltage violations are found for definite2 (B), followed by definite2 (A), inverse and linear. When looking at the time outside bandwidth, the situation becomes more ambiguous (cf. Figure 9). If tight regulation is required (number of tap changes > 250) all control strategies are similar. The definite2 timer seems to perform slightly better in minimizing the time outside band width. For smaller number of tap changes, however, the curves in Figure 9 differ significantly and the simple definite timer most effectively minimizes the time outside band width. For example, the definite timer with $t_{delay} = 40$ s and the definite2-A timer with $t_{delay} = 80$ s both result in 190 tap changes per day. The time outside bandwidth, however, is 25% higher for the definite2-A timer (7% compared to 5.6%).

For comparison of the different reset options in Figure 11 and Figure 12 a definite time delay has been used. The delay reset and delay freeze reset timer use $t_{reset} = 0.5 t_{delay}$. Simulations with $t_{reset} = t_{delay}$ and $t_{reset} = 2 t_{delay}$ yielded similar or worse performance than $t_{reset} = 0.5 t_{delay}$. As can be seen from Figure 11

and Figure 12 the reset options do not have a large impact on the performance of the control algorithm. The integrating reset and delay freeze reset timer are slightly better than the traditional instantaneous reset timer. The delay reset timer does not exhibit any advantages.

CONCLUSIONS

Tap changing transformers are expected to play a major role in the integration of renewable energy into the distribution grid and the findings of the current studies provide guidance on how to control them.

On a clear day it is usually not possible to reduce the number of tap changes and small time delays (e.g. $t_{delay} = 10s$) produce best results. For cloudy days there is a trade-off between minimum number of tap changes and compliance with the permissible voltage band. Regulation requirements and the resistance to wear and tear of the OLTC devices influence the optimal setting of the time delay.

The magnitude of the voltage fluctuations can be significantly reduced by using definite2 type timers instead of simple definite timers.

If only the time outside bandwidth is of concern, traditional definite instantaneous reset timers generally show a good performance. Small improvements are possible with the integrating reset and delay reset options.

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