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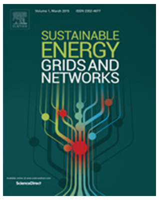

Local identification of voltage instability from load tap changer response

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ABSTRACT

This paper presents a local long-term voltage instability monitoring method, which is suitable for on-line applications. The proposed extended-time Local Identification of Voltage Emergency Situations (eLIVES) method is a significantly modified version of the previously presented LIVES method. The new method is not bound to assessing system response over a predefined LTC tapping period. This allows handling LTCs with variable delays, as well as events taking place during the tapping sequence impacting the distribution voltages. For that purpose, eLIVES applies recursive least square fitting to acquired distribution voltage measurements and a new set of rules to detect a voltage emergency situation. The effectiveness of the eLIVES method is presented on the IEEE Nordic test system for voltage stability and security assessment.

1. Introduction

Since the blackouts that took place in the 80's (e.g. [1]), voltage instability in power systems has been intensively studied [2,3]. Liberalization of the electricity markets has put pressure on power systems and is likely to result in operating conditions closer to stability limits in the near future. For this reason, an early and reliable identification of developing instabilities or emergency conditions will become crucial to operate power systems securely. A widespread practice for voltage stability monitoring is to observe the voltage magnitudes at certain key transmission buses and issue an alarm, when they drop below pre-defined critical thresholds. For this approach, a major challenge is to define appropriate thresholds valid for a wide range of disturbances. Recent research efforts have been focusing on more accurate on-line voltage stability monitoring and early detection of developing voltage instability. The aim of these methods as well as the one proposed in this paper is to identify an evolving instability before it is apparent from sole observation of bus voltage magnitudes. A review of existing voltage instability detection methods has recently been published in [4]. The developed methods are either attempting to detect voltage instability on a system-wide level or purely locally. Detection methods utilizing wide-area measurements are, for example, based on decision trees [5] or suitable voltage stability indices [6–8]. Some of the system-wide methods require full system observability obtained from PMUs, which is not yet available. However, a combination of PMUs with SCADA measurements can already today provide full system observability.

Local methods require only locally available measurements, which are easily accessible. A group of local methods attempts to determine voltage stability through detection of the impedance matching condition [9–11]. Another local method, called Local Identification of Voltage Emergency Situations (LIVES) [12,13], is utilizing measurements, which are readily available in the Load Tap Changer (LTC) controlling bulk power delivery transformers. In order to early detect voltage instability, LIVES solely monitors the voltage magnitude on the controlled, distribution side of the transformer. This voltage is not only affected by the local LTC, but reflects the combined effect of all voltage controllers in the system, e.g. other LTCs, OverExcitation Limiters (OELs) and shunt capacitor switching. Fig. 1 shows an example of a voltage magnitude at a Medium Voltage (MV) bus, the ratio of the local transformer and the voltage magnitude at the corresponding High Voltage (HV) bus. It can be observed that the voltage magnitude at the HV bus is declining after the initial outage, under the effect of multiple tap changes (including the one shown in Fig. 1). After the initial oscillations of the MV voltage, induced by a fault and its clearance, damped out, it can be observed that each tap change in

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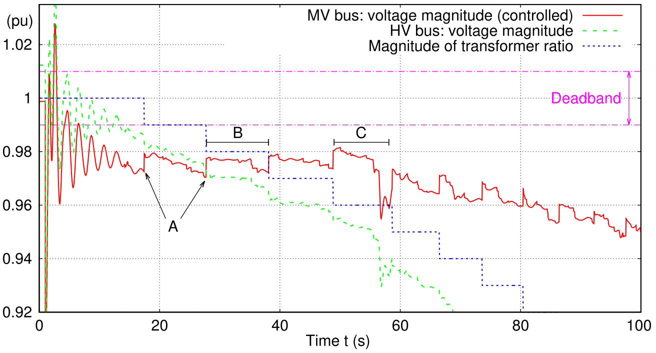

Fig. 1. Example of combined effect of local LTC and other voltage controllers in a voltage long-term voltage unstable evolution after a line outage. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the shown transformer (identified by the jumps in the dashed blue curve) temporarily increases the corresponding MV bus voltage magnitude (see *A* in Fig. 1). This temporary increase is to some extent canceled by the effect of other tap changers as well as field current limiters. An almost complete cancellation of the benefit of the local tap change can be observed in the time interval marked *B* in Fig. 1, while during the period marked *C*, the other tap-changes and field current limitations clearly prevail. From this time on, an overall negative trend of the distribution voltage magnitude can be observed, which is typical for long-term voltage instability.

The early detection of the above unsuccessful distribution voltage restoration is the topic of this paper. It should also be mentioned that, in near future, the response of active distribution grids will play a role in voltage recovery. However, in this paper the focus is on the effect of load tap changers.

The LIVES method described in [12] relies on the assumption that LTCs apply a constant tap delay. On the contrary, this paper proposes an approach that encompasses the case when LTCs have variable tap delays, e.g. obeying an inverse time characteristic, where the tap delay decreases with an increasing deviation of the controlled voltage from its set-point (as in the example of Fig. 1).

The development of the proposed extended-time LIVES (eLIVES) method was motivated by the idea of considering the whole distribution voltage recovery after an unforeseen event instead of looking at an incremental behavior over one tapping period.

The paper is structured as follows. In Section 2 the original LIVES method [12] is summarized and reasons for its non-applicability in the case of variable-delay LTCs are presented. In Section 3, the recursive least squares approach, which is used to fit a linear regression model to the voltage evolution at the LTC controlled bus, is explained. Then the rules used for the detection of a voltage emergency situation are introduced. The IEEE Nordic Test System used for the validation of the proposed method as well as the obtained simulation results of the identification of voltage emergency situations are discussed in Section 4. In Section 5 an application of eLIVES to emergency control is presented and Section 6 presents an assessment of the methods robustness, when noise is added to the measurement samples. Finally, some concluding remarks are offered in Section 7.

2. Principle and limitations of the LIVES method

The LIVES method [12] relies on the individual monitoring of distribution transformers, equipped with LTCs. Essentially, the method identifies an evolving long-term voltage instability through the fact that the positive effect on the controlled voltage of a local tap change is canceled by tap actions of other transformers and similar events in the system.

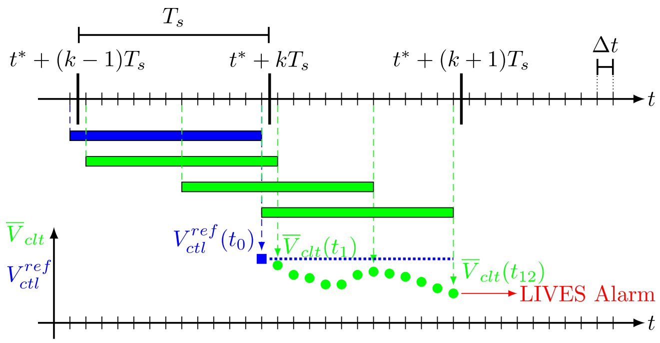

Fig. 2. Visualization of the MA calculation in LIVES at an LTC with constant tap delay T_s. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

For that purpose, LIVES observes the controlled voltage over a time interval including a single tap change of the local transformer. To filter measurement noise and transients, a Moving Average (MA) of the voltage is computed. The MA's sliding window size is chosen equal to the time between two tap changes. Fig. 2 is used to explain how MA computation and monitoring work. On the upper time line, the shorter vertical ticks indicate the discrete times, where voltage measurement samples are collected. The sample rate is Δt. The longer vertical ticks depict times at which tap changes occur in the monitored transformer. It is assumed that the LTC applies a constant delay T_s between successive tap changes and that the controlled voltage does not re-enter the deadband during the displayed time period. t^* corresponds to the time of the first tap change; hence, the subsequent tap changes occur at t^* plus a multiple of T_s. The blue and green bars correspond to the time window, used to compute the respective MA. On the lower time line, the shorter vertical ticks again show the discrete times, where samples are collected. On the ordinate, the computed MA of the controlled voltage ($\overline{V}_{ctl}$, green circles) and a reference value (V_{ctl}^{ref}, blue squares) are shown.

The implementation of LIVES can be summarized as follows [13].

1. Before a tap change, e.g. at the discrete time t_0, the Moving Average $\overline{V}_{clt}(t_0)$ of the controlled voltage V_{ctl} is calculated as follows:

   $$\overline{V}_{clt}(t_j) = \frac{1}{n}\sum_{k=0}^{n-1} V_{ctl}(t_j - k\Delta t) \tag{1}$$

   where n is the number of samples involved. In order to ensure that only one tap change is included in the computation of the MA, n is computed to correspond to the constant tap delay T_s of the respective LTC:

   $$n = \left\lceil \frac{T_s}{\Delta t} \right\rceil. \tag{2}$$

   This MA is stored as a reference value.

   $$V_{ctl}^{ref}(t_0) = \overline{V}_{clt}(t_0). \tag{3}$$

2. At every sampling step $t_j = t_0 + j\Delta t$ $(j = 1, \dots, n)$ the MA is updated using (1). It is then compared to V_{ctl}^{ref}. If the MA exceeds this reference, (indicating that voltage is recovering) no further check is going to be performed until a new reference is computed. On the other hand, if the MA remains below the reference for a period of at least T_s an alarm is issued.
3. Before the next tap change and if the MA at some point exceeded the reference, a new reference is taken equal to the MA just before the tap and the monitoring is continued as described above.