Fuzzy Logic Controller to Improve the Coordination of Cascaded Tap Changers

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Abstract: The transformers which connect the different voltage levels in transmission and distribution systems are supplied with on-load tap changing mechanism. The on-load tap changer maintains the voltage amplitude within the predefined limits at the so-called regulation bus. In a radial feeder, the on-load tap changers are cascaded. Poor coordination between cascaded tap changers causes improper voltage profile and unnecessary operations of tap changers. A fuzzy logic controller is presented in this paper which improves the operation of cascaded tap changers as well as parallel ones. The proposed controller monitors both primary and secondary voltages of the transformer and orders an upward or downward tap changing operation. Because of locally measurement, the communication is not required between two substations which are apart. The controller is also able to set the time delay of tap changing operations based on the measured voltages, which improves the performance of controller and provides a chance to reduce the unwanted changes of taps and also an opportunity to correct the voltage in a reasonable time.

Key words:

INTRODUCTION

Voltage profile in a distribution feeder should be within the pre-defined limits. Due to load variation, the deviation of voltage amplitude from desired value may exceed the permissible value.

In general, there are two ways to regulate the voltage, injection of reactive power and direct control of voltage amplitude. The second method can be established utilizing on-load tap changer transformer (OLTC).

Because of multiple voltage levels, the cascaded OLTCs are required and because of different load points with the same voltage the parallel OLTCs are required. In nowadays systems, there are several OLTCs which regulate and control the voltage profile of feeders. If the control of the OLTCs is not coordinated then poor voltage regulation and unnecessary operation of OLTCs may occur.

The main goals for the control algorithm of OLTCs are:
- Reduction of voltage deviation at regulated bus, which is achieved by changing the tap of transformer.
- Preventing operation of OLTC under specified conditions such as short circuit faults, transformer overload, etc.
- Reduction of tap changing operation as much as possible, to keep long life time of OLTC and reducing the maintenance cost of OLTC.

The first target and the third one are in opposite orientation. In the other hand, the first target means that the OLTC should operate and react quickly while the third target means that operation should be restrained as possible. So the controller should achieve a trade-off between the quality of the voltage profile and the number of tap changing operations.

The switching of the tap changer is controlled automatically by an Automatic Voltage control Relay (AVR).

Conventional AVR uses a constant time delay in ordering a tap operation, to filter temporary voltage deviation and consequently to eliminate the unwanted operations. To improve the performance of conventional AVR, an inverse-time characteristic is utilized [AREVA-Kasztenny]. So a conventional AVR can be shown as a state diagram and an inverse-time characteristic for time delay. Fig. 1 shows the state diagram and the time delay curve [Larsson1].

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Fig. 1: a) state diagram and b) the characteristic of time delay AREVA which explain the operation of conventional AVR.

Detailed descriptions can be found in [Larsson2, Larsson1, Kasztenny]. If the time delay of cascaded OLTCs are similar then all series OLTCs operate simultaneously after any voltage fluctuations at supply side. Considering typical network shown in figure 2, it can be indicated that if any voltage reduction occurs at supply side (point A) then all OLTCs (T1, T2, and T3) change their own tap to regulate the voltage. After the operation of OLTC T1 the primary voltage of T2 and T3 are corrected. After this T2 and T3 have to correct their previous tap change and revert back to the original tap position.

With coordinated control of OLTCs it is possible to reduce the number of, or eliminate counteracting tap operation. Consequently, the total number of operations and the number of voltage spikes due to OLTC interactions would decrease. Wear on the tap changer mechanism is the most common reason for transformer maintenance and therefore a reduction of the number of tap operations made is highly desirable.

A tuning rule that ensures the proper coordination of cascaded OLTCs using conventional controllers is presented in [Larsson1]. A fuzzy logic controller (FLC) for one OLTC in a distribution network is presented at [Kasztenny]. The proposed scheme in [Kasztenny] is very good for control one OLTC, but there is no idea to coordinate cascaded OLTCs. In [Larsson2], an FLC that coordinates tap operations at different voltage levels is proposed. A prototype of FLC has been constructed and installed and successfully tested in a distribution feeder which its results are in [Larsson]. In [Larsson2] communication is used between different voltage levels to coordinate the OLTCs. Another approach which improves the performance of OLTCs operating in series is in [smith]. This controller uses local measurements for control of OLTCs and no communication is needed.
This can reduce the complex connectivity of system components. In the following sections these schemes are analyzed concisely and their merits and drawbacks are described.

**A- Conventional Control Scheme with Revised Tuning [Karlson]:**

The tuning rule for cascaded OLTCs in radial network is to assign longer delay time for lower level units. The tuning rule has been verified in simulations and field measurements, and it is shown that the number of tap operation is reduced by 20%, compared to conventional tuning.

The property of this scheme is as follows:

- Local control system, no need for communication
- Preserves the existing control
- Some selectivity can be achieved
- Robust, no model needed
- Difficult to tune, fixed time delay after tuning
- Slow customer side voltage restoration

It can be deduced from figure 3 that the voltage at customer side is regulated more slowly than that of the source side. In the other hand, at the same instant, larger voltage deviation is corrected slowly. Beside this, the tap operation of the upstream OLTC is more than that of the downstream one, because of shorter time delay of upstream OLTC. Considering that upstream OLTC is more expensive, it is not suitable for this OLTC to operate more than the other.

**Fig. 3:** Longer time delay as OLTC is closer to load point, in revised tuning scheme.

**B- Fuzzy-Rule-Based Controller, Coordinated OLTCs [mat]:**

The fuzzy-rule-based controller reduces the number of OLTCs operation in test system by some 36%, compared to revised conventional control scheme. A fuzzy-rule-based controller which is a centralized tap changer control is installed in the distribution system at Österlen in southern Sweden. The main idea in this scheme is as following:

"In mediocre voltage fluctuations, while upstream OLTC is about to regulate the voltage, the downstream OLTCs have to cancel their operations."

So the main property of this scheme is:

- No model of the system is needed
- A communication between substations and centralized controller is needed.
- Again the more expensive OLTC, upstream one has to operate more than the others.
- There is no idea for coordinating the load side OLTCs which are at parallel feeders.
- Fixed time delay, after tuning

The advantage with using communication is that the time delays can be minimized therefore enabling the downstream controller to have a faster reaction, but more complex connectivity occurs and extending the system is difficult.
C- Coordination Without Communication [smith]:
   When a tap changer detects a voltage deviation it is the result of two possibilities:
   - A system voltage change above the tap changer
   - A load change downstream of the tap changer

   If a tap changer experiences a load change then it should correct the voltage itself. But when a voltage
deviation takes place without any load change then this OLTC should wait until the upstream OLTC proceeds
to correct the voltage. In this scheme, the OLTC current is measured to detect load change. The current is not
proper for detecting load change. Considering an upstream OLTC makes a tap operation then the primary and
also the secondary voltage of downstream OLTC will change and consequently the current of the downstream
OLTC will change. Now the downstream OLTC is to operate because of current change, while the load does
not change in fact and the controller is in mistake.

D- Adaptive Time Delay, No Coordination [mohan]:
   The particular property of this fuzzy logic controller is adaptable time delay which provides a chance to
reduce the unwanted changes of taps and also an opportunity to correct the voltage in a reasonable time. But
there is no idea for coordinating the OLTCs which operate in series.

II. Proposed Scheme:
   The properties of different schemes are described in introduction. Gathering the distinguish properties of
these schemes, the proposed scheme is obtained. These properties are as following:
   - No need to system model [Larsson2]
   - Adaptable time delay [Kasztenny]
   - Coordination without communication [smith]
   - Preserve the existing controller [Larsson1]

   Figure 3 indicates that the voltage deviation on secondary bus of T2 is the result of two possibilities:
   - The system voltage above the tap changer (primary voltage) is not proper.
   - The primary voltage is proper but because of the voltage drop on transformer, the secondary voltage is
not proper.

   If the secondary voltage deviation is large but the primary voltage is proper then OLTC should make a
tap to regulate the voltage quickly. But if primary and consequently the secondary voltages are not proper the
OLTC is better to wait till the upstream OLTC corrects the voltage.

   Therefore the basic control rule is as following:
   "If the primary voltage deviation is small, then OLTC should regulate the voltage quickly.
   If the primary voltage deviation is large then OLTC is better to hesitate in correcting the voltage."

   The proposed scheme is based on voltage measurement. Both primary and secondary voltages of each
OLTC are measured and each OLTC has its fuzzy logic controller (FLC) and these controllers are coordinated.
The adaptable time delay is the other property of this controller.

A- Fuzzy Logic Controller:
   Fuzzy control has been most successfully used for control problems where the control objectives are
difficult to quantify or where one has some heuristic knowledge that can improve control [Larsson2, Kasztenny,
Fabio, Ruey]. The basic idea is that an observation of each physical process variable can be translated to a
fuzzy variable, giving it a linguistic interpretation. This process is usually called fuzzification. A fuzzy variable
has a value between 0 and 1 describing to what extent the observation has the property described by the fuzzy
variable. The fuzzy variables can be manipulated with the fuzzy set operators (\(^\cap\) (intersection), \(\cup\) (union), \(~\) (complement) etc.). So that combinations of fuzzy variables can be formed and used to determine the controller
outputs. They are written as a set of rules on the form:

   \[
   \text{physical variable} \quad \begin{cases} \text{some action} \Rightarrow \text{some property(some variable)} \\ \text{fuzzy controller output} \quad \text{fuzzy variable} \end{cases}
   \]  (1)
The right hand side of (1) may contain several fuzzy variables related by the fuzzy set operations. Together, these rules define the rule-base of the controller and should express the heuristic knowledge one has of the desired controller. The process of evaluation of the rules is called inference. The output of the inference is a fuzzy variable for each control signal. These fuzzy variables have to be translated to physical controller outputs. This translation is called defuzzification. The entire process is a simple mapping from measurements to controller outputs.

**B- Control Problem Formulation:**

By inspection of the voltage profile in a typical network, some heuristic rules can be derived:
- If the voltage deviation at secondary of an OLTC is large but the primary voltage is proper then this OLTC should do a tap operation to regulate the voltage.
- If the primary voltage deviation and consequently the secondary voltage deviation of an OLTC are large then this OLTC has to wait until the upstream OLTC corrects the voltage.
- The larger voltage deviation is, the faster operation is.

So the input signals of the controller are primary and secondary voltages and the outputs are the tap operation and the time delay.

**C- Preserving the Existing Controller:**

It should be noted that in conventional control the secondary current is often used as an input variable. In the proposed it is possible to replace the primary voltage with the secondary current. The primary voltage can be easily calculated with secondary voltage, secondary current, and short-circuit impedance of the transformer. Therefore the conventional scheme can be easily extended to the proposed scheme without emerging any extra measuring device. The next step is to convert the linguistic variables to the fuzzy sets.

**D- Membership Functions:**

In [mat] a detailed expression for adjusting the membership functions of the voltage deviation is presented. The controller recognizes the following levels of the input and output signals:
- Voltage deviation: negative large (HNEG), negative (NEG), zero (ZER), positive (POS), and positive large (HPOS).
- Direction of tap changing: up (UP), do not change (UC), and down (DN).
- Time delay: small (S), medium (M), and large (L).
- The signals are converted to above fuzzy sets using the membership functions shown in figure 4.

![Fig. 4: Membership functions of the fuzzy sets used for linguistic variables involved in the proposed scheme.](image-url)
E- The Rule Base:

According to the above paragraphs, one can defines 25 control rules for each output. Some of these rules are as following:

If \((\Delta V_1 \text{ is } HN) \text{ AND } (\Delta V_2 \text{ is } HN)\) THEN: \((TAP \text{ is } DN) \text{ AND } (Td \text{ is } L)\)

If \((\Delta V_1 \text{ is } N) \text{ AND } (\Delta V_2 \text{ is } HN)\) THEN: \((TAP \text{ is } DN) \text{ AND } (Td \text{ is } M)\)

If \((\Delta V_1 \text{ is } Z) \text{ AND } (\Delta V_2 \text{ is } HN)\) THEN: \((TAP \text{ is } DN) \text{ AND } (Td \text{ is } M)\) …

If \((\Delta V_1 \text{ is } HP) \text{ AND } (\Delta V_2 \text{ is } HP)\) THEN: \((TAP \text{ is } UP) \text{ AND } (Td \text{ is } L)\)

Where \(\Delta V_1\) and \(\Delta V_2\) are primary and secondary voltage deviations from a predefined value, respectfully. The rule base is summarized in table 1 and 2.

Table 1: Rule base for the time delay of the FLC

<table>
<thead>
<tr>
<th>(\Delta V_1)</th>
<th>HN</th>
<th>N</th>
<th>Z</th>
<th>P</th>
<th>HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta V_2)</td>
<td>L</td>
<td>M</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>N</td>
<td>L</td>
<td>M</td>
<td>S</td>
<td>S</td>
<td>S</td>
</tr>
<tr>
<td>Z</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>P</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>M</td>
<td>L</td>
</tr>
<tr>
<td>HP</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>M</td>
<td>L</td>
</tr>
</tbody>
</table>

Table 2: Rule base for the direction of change of the FLC

<table>
<thead>
<tr>
<th>(\Delta V_1)</th>
<th>HN</th>
<th>N</th>
<th>Z</th>
<th>P</th>
<th>HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta V_2)</td>
<td>DN</td>
<td>DN</td>
<td>DN</td>
<td>DN</td>
<td>DN</td>
</tr>
<tr>
<td>N</td>
<td>DN</td>
<td>DN</td>
<td>DN</td>
<td>DN</td>
<td>DN</td>
</tr>
<tr>
<td>Z</td>
<td>UC</td>
<td>UC</td>
<td>UC</td>
<td>UC</td>
<td>UC</td>
</tr>
<tr>
<td>P</td>
<td>UP</td>
<td>UP</td>
<td>UP</td>
<td>UP</td>
<td>UP</td>
</tr>
<tr>
<td>HP</td>
<td>UP</td>
<td>UP</td>
<td>UP</td>
<td>UP</td>
<td>UP</td>
</tr>
</tbody>
</table>

III. Simulation Results:

To compare the proposed scheme with the other schemes a test system is simulated. The original network is a branch of the distribution system at a rural area in the Southeast Sweden [Larsson1, Larsson2]. To study the parallel OLTCs, another feeder denoted by ÖTP2 is added to 20kV bus which is parallel to existing 10kV feeder. Figure 6 shows the test system and its parameters are in table 3.

Table 3: Parameter value for test system.

<table>
<thead>
<tr>
<th>OLTC data</th>
<th>Min tap</th>
<th>Max tap</th>
<th>Tap step</th>
<th>Uflection (Dead band)</th>
<th>Ureset</th>
<th>Td</th>
</tr>
</thead>
<tbody>
<tr>
<td>TLA</td>
<td>1</td>
<td>19</td>
<td>1.67%</td>
<td>1.50%</td>
<td>1.35%</td>
<td>120 S</td>
</tr>
<tr>
<td>JSD</td>
<td>1</td>
<td>9</td>
<td>2.50%</td>
<td>2.25%</td>
<td>2.00%</td>
<td>120 S</td>
</tr>
<tr>
<td>ÖTP1</td>
<td>1</td>
<td>17</td>
<td>1.67%</td>
<td>1.50%</td>
<td>1.35%</td>
<td>120 S</td>
</tr>
<tr>
<td>ÖTP2</td>
<td>1</td>
<td>17</td>
<td>1.67%</td>
<td>1.50%</td>
<td>1.35%</td>
<td>120 S</td>
</tr>
<tr>
<td>Network</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z (p.u.)</td>
<td>(\theta_1) (rad)</td>
<td>(\theta_2) (rad)</td>
<td>(\theta_3) (p.u.)</td>
<td>(\theta_4) (rad)</td>
<td>(\theta_5) (rad)</td>
<td></td>
</tr>
<tr>
<td>0.0561</td>
<td>1.3369</td>
<td>0.0953</td>
<td>1.5584</td>
<td>0.6796</td>
<td>1.3486</td>
<td>2.663</td>
</tr>
<tr>
<td>p.u. conversion data</td>
<td>Vbase (130kV level)</td>
<td>Vbase (50kV level)</td>
<td>Vbase (20kV level)</td>
<td>Vbase (10kV level)</td>
<td>Sbase</td>
<td></td>
</tr>
<tr>
<td>132 kV</td>
<td>55 kV</td>
<td>22 kV</td>
<td>10.7 kV</td>
<td>100 MVA</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

To assess the performance of proposed FLC, a comparison between six different schemes is presented in table 4:

Table 4: The properties of different schemes (Vs, Vp and Is denote secondary, primary voltages, and secondary current, respectfully.)

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Input</th>
<th>Output</th>
<th>Comm.</th>
<th>time delay</th>
<th>Coordination</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCN</td>
<td>Vs</td>
<td>Tap</td>
<td>No</td>
<td>Fixed</td>
<td>No</td>
</tr>
<tr>
<td>CCR</td>
<td>Vs</td>
<td>Tap</td>
<td>No</td>
<td>Fixed</td>
<td>Rather</td>
</tr>
<tr>
<td>FBR</td>
<td>Vs–Utap(^1)</td>
<td>Tap</td>
<td>Yes</td>
<td>Fixed</td>
<td>Yes</td>
</tr>
<tr>
<td>FLC</td>
<td>Vs – Utap(^2)</td>
<td>Tap–Td</td>
<td>No</td>
<td>Adapt.</td>
<td>No</td>
</tr>
<tr>
<td>NCom</td>
<td>Vs - Is</td>
<td>Tap</td>
<td>No</td>
<td>Fixed</td>
<td>Yes</td>
</tr>
<tr>
<td>PRP</td>
<td>Vp-Vs</td>
<td>Tap - Td</td>
<td>No</td>
<td>Adapt.</td>
<td>Yes</td>
</tr>
</tbody>
</table>

\(^1\) tap of upstream OLTC
\(^2\) last tap of OLTC
Fig. 5: The control surfaces for a) tap change and b) time delay.

- Conventional control scheme with normal tuning, i.e., all OLTCs have time delays of 120 s (CCN) [Larsson1, Larsson2].
- Conventional scheme with revised tuning, i.e., the top level OLTC has a time delay of 30 s, the middle one has 70 s, and the lower level OLTCs have 150 s (CCR) [Larsson1, Larsson2].
- Fuzzy rule-based control scheme proposed in [Larsson2] (FBR).
- Fuzzy logic controller proposed in [Kasztteny] (FLC).
- Coordinated controller without communication, as in [smith] (NCom).
- Proposed scheme (PRP)
FLC has good performance in control of one OLTC, but it does not provide any coordination in a system with several OLTCs. Therefore it is deleted from the list. Also [smith] did not present any idea to cover the problems arise from current measurement, so that NCom is deleted from the list too.

Three different scenarios are simulated:
- Capacitor bank switching
- Step change on ÖP2 load
- Continuous variations of TLA load

The simulation results are summarized in table 5.

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Cap. switch</th>
<th>Load change in TLA</th>
<th>Load change in OTP</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCN</td>
<td>12</td>
<td>58</td>
<td>16</td>
</tr>
<tr>
<td>CCR</td>
<td>10</td>
<td>40</td>
<td>12</td>
</tr>
<tr>
<td>FBR</td>
<td>14</td>
<td>31</td>
<td>20</td>
</tr>
<tr>
<td>PRP</td>
<td>12</td>
<td>31</td>
<td>18</td>
</tr>
</tbody>
</table>

To compromise the performance of different schemes a voltage deviation criterion is defined. This criterion is derived from the standard deviation of voltage at several buses. Relation (2) defines $\overline{\Delta V}$:

$$\overline{\Delta V} = \frac{1}{T} \int_{t_0}^{T} f(\Delta V) dt,$$

Where $V_i$ and $V^*$ are the voltage at $i$-th bus and reference voltage, respectively. The function $f$ is shown in figure 7.

It can be evident that CCR regulates the voltage with less tap operation in respect to CCN (table 5). A medium time delay (70 s) is tuned for FBR. The simulation results indicate that when the source of voltage fluctuation is at the top level, FBR can reduce the unwanted tap changing. If the source of voltage fluctuation is in lower level then FBR cannot perform the rule of reducing tap operation as successfully as previous case (table 5).

The performance of PRP resembles to FBR. But the merit of PRP is that it does not need communication. Also PRP can easily be substituted for existing AVR.

In some cases, such as load change in TLA, tap operation made by PRP and FBR is more than that of CCR and CCN. Considering $\overline{\Delta V}$ criterion the reason of more operations is justified. The voltage deviation and tap operation of different scheme, which are obtained by simulation are in appendix.

IV. Conclusion:

This paper presents a fuzzy rule-based controller for coordinating cascaded tap changer transformers in distribution system. The properties of this controller are as follows:
- Local control system, no need for communication
- Can easily be substituted for existing AVR and preserves the existing control
- Robust, no model needed
- Adaptable time delay which provides the chance to regulate the voltage in a reasonable time

The proposed scheme has been simulated and the simulation results show the ability of the controller in reducing unwanted tap operations as well as voltage deviation.

ACKNOWLEDGMENT

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REFERENCES


Appendix:

Fig. a-1: The voltage and tap operation of Conventional Controller (CCN) after capacitor bank switching.
Fig. a-2: The voltage and tap operation of revised Conventional Controller (CCR) after capacitor bank switching
Fig. a-3: The voltage and tap operation of Fuzzy Rule-Based Controller (FBR) after capacitor bank switching.

Fig. a-4: The voltage and tap operation of Proposed Controller (PRP) after capacitor bank switching.