Digitalization of Regulation Unit Selection Process in Power Transformer Design

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ABSTRACT – Large power transformers generally include a customer request for a technically appropriate regulation unit. The selection process of the regulation unit consists of defining the required input data, performing mathematical calculations necessary to find the technical limit values that the regulation unit has to satisfy, and finally optimizing and selecting the appropriate regulation unit.

The regulation unit is defined by the tap changer type, number of phases, maximum rated through current, insulation level, tap selector size, number of positions and type of regulation. Each of these items is mutually dependent and may have an impact on the restrictions of other items (according to the manufacturer’s technical data). Taking this into consideration, the number of possible permutations for selecting the appropriate regulation unit consists of thousands of different combinations, depending on the type of regulation and other technical limitations.

The process of finding the optimal regulation unit “manually” can take up to several hours. Implementing the developed algorithm and introducing Tap Changer Selection application, the required time is reduced to several minutes, which represents significant time savings and reduced possibility of errors during power transformer design process.

Keywords – Power transformer regulation, tap changer selection, tap changer database, tap changer calculations

I. INTRODUCTION

Large power systems such as electrical grids of entire cities, countries or continents are systems which must be continuously regulated in order to keep the voltage supply constant, thereby ensuring all the electrical devices and equipment to work in the expected voltage range. In such large systems, disturbances in the load and/or supply is inevitable – i.e. under greater load, the current increases, and consequently the voltage drops along the transmission lines which connect the power supply to the power consumption. Handling such disturbances and maintaining a constant voltage supply is (among others) the responsibility of the power transformer as one of the most expensive parts of the power grid. For this purpose, the regulating power transformer is equipped with a regulating winding which is connected to the regulation unit – usually On Load Tap Changer (OLTC). The voltage regulation basic principle is adding or subtracting turns from either the primary or the secondary winding. The task of an OLTC is the current break function when transformer is energized and in service. As opposed to the OLTC, the DETC (De-Energized Tap Changer) must not be operated while the transformer is energized. This means that for the DETC to operate, the transformer must be disconnected from the network for a short period of time. This is why an OLTC regulation unit is more and more becoming a standard customer request for power transformer regulation.

Generally, many different regulation units are technically appropriate and may be used for a particular transformer design. In order to minimize the overall costs while still managing to provide the required regulation capabilities, one of the transformer manufacturers’ challenges is to optimize the regulation unit selection process. Since the regulation unit (i.e. tap changer) can make around 10 – 20% of the total material cost of the transformer, the overall effect of optimizing the regulation unit becomes significant.

II. RELATED WORK AND MOTIVATION

Related work on this area consists of different power transformer design tools which (at most) consist of a regulation unit database, expecting the user to choose the appropriate regulation unit from the list (manually). A tool example presenting automated regulation unit selection functionality in the power transformer industry is ABB Compas tool [5]. Since this tool is limited only to ABB types of tap changers, the main motivation for this work was to provide a faster and more efficient way of selecting the optimal regulation unit also for manufacturers other than ABB, e.g. MR (Germany) and C.A.P.T. (Italy) for OLTC and DETC regulation units since this is a common customer request. The main advantage of this application becomes evident in the offer stage where quick and correct selection of the optimal regulation unit is important for the final transformer design cost estimation.

1. Three-limb core
   2. LV Winding
   3. HV Winding
   4. Tapped Winding
   5. Tap Leads
   6. LV Bushings
   7. HV Bushings
   8. Clamping Frame
   9. On-Load Tap Changer
   10. Motor Drive
   11. Tank
   12. Conservator
   13. Radiators

Figure 1: Power transformer with a regulation unit
III. MANUAL SELECTION AND CALCULATIONS

Each type of regulation unit is available in a number of variants, with different values of maximum rated through-current, number of phases, highest insulation level, tap selector size and basic connection diagrams. Therefore, the type designation (examples in Fig. 6) of a regulation unit depends on these features.

When selecting the appropriate type of OLTC or DETC manually, a number of parameters and technical limits have to be considered.

First of all, the rated through current of the regulation unit must not be less than the transformer highest current value of the regulating winding. For regulation at the neutral end with constant induction (constant flux voltage variation, CFVV), the rated through current in case of a three-phase full transformer is:

\[ I_{\text{max}} = \frac{S_n \times 1000}{\sqrt{3} \times U_{1\text{min}}} \]  

where:

- \( I_{\text{max}} \) is the maximum rated through current [A];
- \( S_n \) is the transformer rated power [MVA];
- \( U_{1\text{min}} \) is the rated line voltage in the minimum tap position in [kV].

For a three-phase autotransformer with regulation in neutral end, variable induction (variable flux voltage variation, VFVV), \( S_n = \text{const} \), the rated through current depends on both regulated and non-regulated voltage levels:

\[ I_{\text{max}} = \frac{S_n \times 1000}{\sqrt{3} \times \left( \frac{1}{U_{2\text{min}}} - \frac{1}{U_1} \right)} \]  

where:

- \( U_1 \) is the rated line voltage of the non-regulated side in [kV];
- \( U_{2\text{min}} \) is the rated line voltage in the minimum tap position in [kV].

In case of one-phase transformer, the rated through current is multiplied by a factor of \( \sqrt{3} \) since the rated power is per phase and the rated voltages are phase voltages.

Maximum rated through current is the current which the regulation unit is transferring from one tap to the other at relevant step voltage.

Step voltage \( U_{\text{step}} \) [V] is the phase voltage between the taps which depends on the required regulated voltage range and the required number of positions. This value is constant in case of CFVV (constant flux voltage variation), unlike in the case of VFVV (variable flux voltage variation) where different regulating positions have different volt/turn ratio and therefore different step voltage values:

\[ U_{\text{step}} = \begin{cases} \frac{U_{\text{max}} - U_{\text{min}}}{\sqrt{3}(n-1)} \times 1000 & \text{CFVV regulation} \\ \max(U_k - U_{k-1}) & \text{VFVV regulation} \end{cases} \]  

where:

- \( U_{\text{max}} \) and \( U_{\text{min}} \) are the required maximum and minimum regulated line voltage in [kV] (equivalent three-phase bank line voltage in case of a single-phase transformer);
- \( n \) is the required number of regulating positions (including the rated position);
- \( U_k - U_{k-1} \) is the (phase) voltage [V] difference in the regulating position \( k \) and \( k-1 \) (for positions \( k = 2 \) to \( n \)).

The required regulation unit external insulation level depends on the insulation level to ground of the side where the regulation unit is connected. The withstand voltages of the external insulation are standardized by international standards and correspond to the highest voltage for equipment [4]. In case of regulation in neutral end (common for full transformer or VFVV autotransformer), the insulation level is usually the same as the insulation level of the transformer neutral (unless otherwise specified). In case of regulation in line (common for CFVV autotransformers), the insulation level is the same as the lower voltage side to which the regulation unit is connected. The insulation level has to be checked against the applicable technical guide.

The internal insulation level affects the regulation unit tap selector size, whose price can vary significantly, meaning that the proper selection is of the essence in choosing the optimal regulation unit. Highest operating voltage across the regulating winding is the value that has to be compared with the highest permissible phase service voltage across the regulating winding described in the technical guide, which defines several internal insulation distances to be checked, most important of which are distances ‘a’ and ‘b’. For insulating distance ‘a’ between start and end of the regulating winding and insulating distance ‘b’ between the fine tap selector contacts of different phases, a statistics-based estimation is used. The logic behind the estimation is assuming linear distribution, and additionally applying a „non-linearity“ factor depending on the regulation concept (reg.in main / coarse-fine / reversing / linear) and transformer type (full / auto). The mentioned factor is determined using statistical analysis derived from experimental data. The differences in factors arise from the specifics of the distribution of electrical field in various power transformer types:

- If regulation concept is regulation in main, then the voltages are estimated as:
  \[ ACa = AC \times \frac{RR_{+\%} + RR_{-\%}}{100} \]  
  \[ LJa = 2 \times LI \times \frac{RR_{+\%} + RR_{-\%}}{100} \]  

- If regulation concept is linear regulation, then the voltages are estimated depending on the transformer type:
  \[ ACa = AC \times \frac{RR_{+\%} + RR_{-\%}}{100} \]  
  \[ LJa = \begin{cases} 2.35 \times LI \times \frac{RR_{+\%} + RR_{-\%}}{100} & \text{full transformer} \\ 3.5 \times LI \times \frac{RR_{+\%} + RR_{-\%}}{100} & \text{autotransformer} \end{cases} \]
If regulation concept is coarse-fine or reversing, then the same logic applies as in the case of linear regulation, with the additional factor of 0.5 due to the existing selector switch (indicated by capital letter 'G' in tap changer type designation, e.g. in Fig. 6) which doubles the regulation range for the same number of steps in regulation winding:

\[ ACa = 0.5 \times AC \times \frac{RR_{+\%} + RR_{-\%}}{100} \quad (8) \]

\[ Lla = \begin{cases} 2.35 \times 0.5 \times LI \frac{RR_{+\%} + RR_{-\%}}{100} & ; \text{full transformer} \\ 3.5 \times 0.5 \times LI \frac{RR_{+\%} + RR_{-\%}}{100} & ; \text{autotransformer} \end{cases} \quad (9) \]

where:

\[ RR_{+\%} \text{ and } RR_{-\%} \] are the regulation ranges in + and – side in [%];

LI and AC are the standardized Lightning Impulse and AC power frequency voltage values in [kV] for the regulated voltage level.

For example, in case of regulation range 400kV +/- 8 x 1.25%, the standardized voltage levels are LI = 1550 kV, AC = 630 kV, and \[ RR_{+\%} = RR_{-\%} = 10\% \]. Other voltage types (Switching Impulse SI and service voltage Upog) and voltage distances \( (c_1 \text{ and } c_2) \) can be calculated in a similar manner using values from [4]. Example values can be found in Table 1. With some winding arrangements (neutral-end in autotransformers and line-end regulation in delta connected windings), very high voltages may occur. These voltages are significantly influenced by the choice of the regulation concept (linear, coarse fine or reversing regulation). In such cases, additional tools are used to determine the electrical field distribution in the power transformer (FEM analysis). Since the tap selector size price varies significantly, this can also be subject to optimization.

The switching capacity \( P_{SN} \) [kVA] determines the capability of the regulation unit to switch between regulation steps. Since the worst case has to be considered, the required switching capacity in the regulation unit is the product of the relevant step voltage and maximum rated through current (both described above):

\[ P_{SN} = \frac{i_{max} \times U_{step}}{1000} \quad (10) \]

The selected regulation unit must be within the switching capacity diagram (example in Fig. 2). Limit values are given in the manufacturer's technical guide and may restrict certain types of tap changers in some cases.

The number of tap positions and the number of contacts have to be considered as well - different types have different maximum regulation range, depending on the regulation concept. A higher number of positions may also increase the voltage stress of the regulating winding, so this has to be taken into consideration (as described in the internal voltage calculations above).
where:

- \( U_{w+} \) and \( U_{w-} \) are the recovery voltages in [kV];
- \( I_{s+} \) and \( I_{s-} \) are breaking currents in [mA];
- \( C_1 \) and \( C_2 \) are the capacitance values in [pF] of the regulating winding (see Fig. 3) which can be approximated assuming cylindrical winding system [2].
- \( U_1 \) is the rated regulated voltage in [kV];
- \( U_p \) is the preselector voltage in [kV] (see Fig. 3);
- \( \omega = 2\pi f \), where \( f \) is the power frequency in [Hz].

The recovery voltage permissible value is the function of the calculated breaking current value. The mentioned \( U_w(I_s) \) function for each tap selector type and size can be found in the technical data of the regulation unit. If the calculated values of recovery voltages are exceeded, it is necessary to install tie-in resistors or select a different tap selector. The installation of the tie-in resistors affects the regulation unit price as well as overall transformer dimensions, so a solution with bigger tap selector size and therefore higher permissible values of recovery voltage should be considered in such cases. Furthermore, the tie-in resistor dimensions are defined by the regulation unit manufacturer specifically for each design, which can cause an additional unwanted time delay in the transformer final design process. For phase shifting transformers, using regulation unit with two-way change-over selector, one can overcome problems during the change-over selector operation and change of winding connections between phases of the system voltage [6].

During power transformer design process, one has to calculate all of the above mentioned values in order to choose the appropriate regulation unit. Also, the selected regulation unit has to satisfy the OLTC type / selector type matrix shown in Appendix 1. Since the goal is also to find the optimal solution (technically as well as economically), this trial and error process can take up to several hours, even for an experienced electrical designer.

### IV. Tap Changer Selection Application and Database

Due to the complexity of the regulation unit technical limits and cross-dependencies between different types, a relational database is developed in such an architecture that an algorithm can quickly go through all of the possible permutations and compare the actual calculated values with every combination of regulation unit's limits. A small part of the relational database tables and relationships architecture can be found in Appendix 2. Also, the database management user interface (UI) is developed in MS Access environment. Within the database, SQL is used for querying data and sending it to the application for further analysis in the TCS algorithm (Tap Changer Selection). The algorithm then compares the queried data with the calculation results which are calculated in the background as thoroughly described in chapter III. The algorithm also takes into account different possibilities of transformer regulation: for example, a three phase transformer can either be regulated with a single three-phase regulation unit or three single-phase regulation units. Furthermore, autotransformer can be designed with regulation in main winding, meaning that the regulation unit does not have a common neutral end. Therefore, autotransformers with such regulation can only be regulated with three single-phase regulation units (three-phase regulation unit requires a neutral end common point). Also, different regulation concepts have different possibilities for number of positions and number of contacts.

All of the mentioned above is automatically checked for every single regulation unit combination queried from the database. This is achieved using a **foreach** loop which (in each step) calls for different modules used for this purpose. All of the modules and functions are developed in C#, following object-oriented software development principles (Model-View-Controller, MVC pattern). The input for the algorithm that is expected from the application user is the same data that the electrical designer uses in power transformer design (MVA rating, rated voltages and required regulation range, regulation concept, connection of regulating winding, LI and AC voltage levels i.e. external insulation levels to ground and number of tap positions), making the application very user-friendly for any power transformer designer. This data model also makes automatic data import from transformer design software very simple. The algorithm output is the list of all the possible solutions for regulation units (tap changers) that satisfy the given input.
The results are finally sorted according to the expected total cost. Therefore, the application user can simply choose the first regulation unit from the generated list knowing that this is the optimal solution. Other regulation units from the list are not optimal but are also technically acceptable. These can be selected in case of a specific request (e.g., higher external insulation level requested by the customer). Finally, a report containing all the calculations together with the technical limits (example values in Table 1) can be generated automatically.

Workflow for the tap changer selection process (from data input to generating report) for the transformer offer stage and for the final order stage is given in Fig. 7.

Table 1: Calculated and limit values for selected regulation unit

<table>
<thead>
<tr>
<th>Regulation unit</th>
<th>Max</th>
<th>Min</th>
<th>Regulated values</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Voltage (V)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Current (A)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Power (kW)</td>
</tr>
</tbody>
</table>

V. WEB INTERFACE

Together with the Tap Changer Selection application, an additional tool is developed for accessing the final order data through a Web interface. The RSB Base application allows reading all the necessary technical data from the ordering data sheets, saves this data to the database and gives the possibility to search, analyze and report in a user-friendly manner. When transferring the data from a fulfilled PDF form (order sheet) to the database, the original document for ordering the regulation unit is uploaded to the server as well. Web application is developed using Model-View-Controller design pattern, Framework 4.5 technology, Bootstrap and Entity-Framework as a data access technology for SQL Server database for this project.

VI. CONCLUSION

The importance of regulation in power transformers shows that optimizing and choosing the appropriate regulation unit may have a significant impact on the transformer overall cost, making it one of the essential parts of power transformer design. In TCS application, dozens of tables and diagrams, as well as hundreds of pages of technical data from different manufacturers are incorporated in the database. Nevertheless, the developed algorithm performs all the calculations and searches through all of the possibilities in a matter of seconds. Also, the application allows printing out a report with all the relevant calculation data and technical limits almost instantly, regardless of the regulation unit manufacturer. This represents significant time savings and reduced possibility of errors during power transformer design process.

REFERENCES

APPENDIX 1: Available combinations of regulation units with the corresponding tap selector sizes for all MR OLTCs

<table>
<thead>
<tr>
<th>Selector type</th>
<th>OLTC type</th>
<th>„MS“ type selector</th>
<th>„M“ type selector</th>
<th>„R“ type (old) selector</th>
<th>„R“ type (new) selector</th>
</tr>
</thead>
<tbody>
<tr>
<td>MS</td>
<td>(all MS OLTCs)</td>
<td>B</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>M</td>
<td>(all M OLTCs)</td>
<td>-</td>
<td>B, C, D, DE</td>
<td>-</td>
<td>RC, RD, RDE</td>
</tr>
<tr>
<td>RM</td>
<td>(all RM OLTCs)</td>
<td>-</td>
<td>C, D, DE</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>R</td>
<td>(all R OLTCs)</td>
<td>-</td>
<td>C, D, E</td>
<td>RC, RD, RDE, RE, RF</td>
<td>-</td>
</tr>
<tr>
<td>VRC, VRE</td>
<td>(all VRC, VRE OLTCs)</td>
<td>-</td>
<td>B, C, D, DE</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>VRD, VRF</td>
<td>Imax &lt; 1600 A</td>
<td>-</td>
<td>-</td>
<td>C, D</td>
<td>-</td>
</tr>
<tr>
<td>VRG</td>
<td>Imax = 1600 A</td>
<td>-</td>
<td>-</td>
<td>E</td>
<td>-</td>
</tr>
<tr>
<td>VRG</td>
<td>Imax = 1600 A</td>
<td>-</td>
<td>C, D</td>
<td>RC, RD, RDE</td>
<td>-</td>
</tr>
<tr>
<td>VM</td>
<td>Imax = 300 A</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>VM</td>
<td>300 A &lt; Imax &lt; 650 A</td>
<td>-</td>
<td>B, C, D, DE</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>VM</td>
<td>Imax ≥ 650 A</td>
<td>-</td>
<td>B, C, D, DE</td>
<td>-</td>
<td>RC, RD, RDE</td>
</tr>
<tr>
<td>VRS, VRM</td>
<td>Imax ≤ 700 A</td>
<td>-</td>
<td>B, C, D, DE</td>
<td>-</td>
<td>RC, RD, RDE, RE, RF</td>
</tr>
<tr>
<td>VRS, VRM, VRL</td>
<td>Imax &gt; 700 A</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>RC, RD, RDE, RE, RF</td>
</tr>
<tr>
<td>VRH</td>
<td>all VRH</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>RC, RD, RDE, RE, RF</td>
</tr>
<tr>
<td>VRX</td>
<td>VRX I 652</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>RES</td>
</tr>
</tbody>
</table>

APPENDIX 2: Relational database architecture

![Relational database architecture diagram]