Design of a Power Electronic Assisted OLTC for Grid Voltage Regulation

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Abstract: High penetration of distributed generation (DG) has led to frequent voltage fluctuations in the distribution network. This project describes the design of a partially rated, power electronic-assisted on-load tap-changing (OLTC) autotransformer. Positive and negative compensation of the grid voltage can be achieved on feeders that have high distributed generation and/or loading. A novel design of taps comprised of several no-load switches and a single semiconductor-mechanical hybrid switch have been proposed, that requires reduced voltage rating and a number of switches. In steady state, the mechanical switch in the hybrid switch conducts the load current resulting in low steady-state losses. During the tap change process, the OLTC uses semiconductor switches, namely insulated-gate bipolar transistor /metal–oxide semiconductor field-effect transistor, thus achieving arc-free tap change and long lifetime of switches. The OLTC system has been customized for both low-voltage and medium-voltage three-phase distribution networks. An open-delta configuration for the medium-voltage application has been proposed that requires only two OLTC units to control all three line voltages.

Keywords: Distributed power generation, four-step commutation, hybrid switch, On-load tap changer (OLTC), series compensation, transformer, voltage fluctuations

I. INTRODUCTION

In recent years, high penetration of distributed generation (DG) driven by photovoltaic (PV) panels in the distribution network has led to frequent voltage fluctuations and over voltages. Voltage control using traditional voltage regulators is unable to cope with this situation as frequent tap changes reduce the life time of the mechanical taps due to arcing. The voltage controls through shunt compensation methods are ineffective and expensive. Series compensation through centralized on-load tap-changing (OLTC) distribution transformers or feeder-specific compensators is hence a suitable strategy for voltage regulation.

OLTC voltage regulators and sub transmission transformer use taps made of mechanical switches that can be operated under load. Under conditions of recurrent voltage fluctuation due to DG, the mechanical switches undergo frequent wear and tear during tap change due to the arcing phenomenon. This results in lower life time of the switches and necessitates repeated maintenance. Nevertheless, these mechanical taps have the advantage of high overload capacity and low on state losses (1,2,3). On the other hand, electronic tap changers use semiconductor switches that do not have any arcing problems. They provide flexibility in operation but suffer from much higher steady-state losses. By combining the advantages of electronic and mechanical tap changers, power-electronic-assisted tap changers are obtained (4,5,6). The basic idea is to use the mechanical switches in steady state to ensure low steady-state losses and semiconductor switches during tap change to provide an arc-free tap-changing process (7,8,9). The high overload capacity of mechanical switches is of advantage if fault conditions occur during steady-state operation. Therefore, the performance of hybrid OLTC for high fault current does not change (10,11).

This project describes the design of a power-electronic-assisted OLTC autotransformer that provides voltage regulation through series compensation. The novel design of the OLTC autotransformer is cost-effective, efficient, and has a long lifetime. Unlike earlier works that use thyristors, back-to-back series-connected insulated gate bipolar transistors (IGBTs) with ant parallel diodes are used for the two electronic switches. Voltage polarity-based four-step current commutation is used for changing between the taps which results in fast commutation without the need for current limiting impedance. The OLTC has been customized for application in medium-voltage (MV) and low-voltage (LV) three-phase distribution networks. A low-level control mechanism and protection scheme is also developed, thus providing a holistic design for building a prototype.

Problem Definition

Consumers receiving power from an electric utility can observe nominal incoming voltage level (e.g. 120V) shift over the course of a day to a small or large degree. There are many factors contributing to the amount of voltage level fluctuation observed including:

i). Location on the local distribution line
ii). Proximity to large electricity consumers.
iii). Proximity to utility voltage regulating equipment
iv). Seasonal variations in overall system voltage levels
v). Load factor on local transmission and distribution system, etc.

Voltage that is too high can cause premature failure of electrical and electronic components (e.g. circuit boards) due to overheating. The damage caused by overheating is cumulative and irreversible. Frequent episodes of mild overheating can result in the same amount of component damage as a few episodes of severe overheating.

OLTC voltage regulators and sub transmission transformer uses mechanical and electronic tap changers to compensate voltage fluctuations. The mechanical tap changing voltage regulator utilizes contactors or brushes along with some type of motorized drive system to change the taps on the secondary of the transformer.

- Mechanical drive components, brushes and contractors require regular maintenance and/or replacement
- Frequent overloads can damage brushes
- Speed of voltage correction correct may not be fast enough for electronic loads because mechanical voltage regulators must physically move components, their speed in correcting output voltage fluctuations is very slow. Mechanical AVRs measure correction time in volts per second so the larger the voltage correction required, the longer the correction will take. Large voltage corrections can take one-half second to tens of seconds – much longer than many modern electronic loads can tolerate.

Tap changing in the mechanical tap-changer generates arc in the contacts of the diverter switches. This arc causes contamination of the oil surrounding the diverter switches and also leads to the erosion of their contacts. Meanwhile, the whole tap changing process in the mechanical tap-changer is basically performed mechanically. Therefore, in the mechanical tap-changers the conditions of oil, contacts and mechanical moveable parts must be examined regularly and are serviced if necessary.

Tap switching voltage regulators tend to have higher maintenance requirements than magnetic induction units since the magnetic induction voltage regulator has few or no brushes or contactors to wear out. With either type, the maintenance requirements are directly related to frequency of voltage correction – the more it moves the more maintenance will be required.

Because maintenance on utility, oil-filled on-load tap changers can be quite expensive, they often have time delays and other capability built into their controls to minimize the frequency of tap changing. These units typically have recommended overhaul intervals ranging from 500,000 to 1,000,000 operations.

In power quality applications, it would be counterproductive to have delays or other limitations on the operation of tap switching or servo induction voltage regulators. Fortunately, these units are usually air-cooled, smaller in size and relatively accessible compared to the utility OLTC.

The typical electronic tap switching voltage regulator works very much like the mechanical tap switching regulator – except that it replaces mechanical servo drives and brushes with solid-state semiconductor switches.

- Poor current overload capacity (except the series transformer design)
- More expensive than mechanical voltage regulators
- They suffer from much higher steady-state losses
- The principle drawback of electronic voltage regulators is the limitation imposed by the SCRs or other power semiconductors. FPS voltage regulators as well as double conversion and UPS units can fail in a matter of hours or days when put in an application with high inrush or overload currents – without exercising due precautions such as sizing for the peak currents.

In this project we use combination of mechanical and semiconductor switches to ensure low steady state losses and to provide an arc-free tap-changing process.

II. PROPOSED SYSTEM

Design of the Proposed OLTC System

The figure 3.1 represents the block diagram of the proposed system. In this the supply side consists of transformer which has taps. No-load switches are connected to each taps. Then a hybrid switch which consists of both mechanical and electronic switches. The current and voltage measured or sensed from the output is used to change the taps. The tap changing helps to control the voltage without exceeding the specified limit. The voltage and the present tap is displayed by the LCD display.

OLTC Design Using No-Load Switch & Hybrid Switch

Eleven different OLTC topologies using conventional two winding transformers and autotransformer were compared on the basis of the voltage and current ratings of the transformer and tap switches and isolation requirements. The OLTC topology shown in Fig. 5.2 with an autotransformer having taps on the load side was chosen as the most suitable. The choice was made on the optimal requirement of component power ratings, isolation needs, and copper savings.
Figure 3.1: OLTC autotransformer using no-load switches (NL1, NL2) and hybrid switch made of two electronic switches BS1, BS2 and a mechanical switch M.L

The use of an autotransformer saves on material and cost, and the throughput power is approximately ten times the transformed power. The autotransformer turn ratio of input to output is 10:11. If the rated input voltage is 1 p.u., then the taps are present on the section of windings from 0.9 to 1.1 p.u. Ten taps are present each of 0.02-p.u. voltage and, thus, the OLTC can provide up to ±10% compensation.

A combination of no-load switches and a single hybrid switch is used to realize the OLTC mechanism. A no-load switch is a mechanical switch that opens or closes under no load. By operating it under no load, it does not have any arcing phenomenon occurring. The idea is derived from —diverter switch—type voltage regulators shown in Fig. 5.3. Here, two movable no-load switches referred to as —selector switch— are used to select the taps and a mechanical —diverter— switch is used for the tap-change process and for carrying the load current in steady state.

Each tap of the autotransformer is connected to a no-load switch, and alternate no-load switches are connected to each other—shown by red and green taps. The taps are, in turn, connected in series to the hybrid switch. For the normal operation of the OLTC, the following conditions are imposed:

1) Mechanical switch conducts the load current in steady state, and bidirectional electronic switches BS1 and BS2 are used for the tap-changing process.
2) At any point of time, only one no-load switch amongst green or red will be closed. This is to prevent the occurrence of a short circuit between the taps and ensure that the maximum voltage that the no-load switches will block in the OFF condition is 0.2 p.u.
3) Tap changes are always made in steps of one. This means that if tap 2 is ON, then a tap change can be made only to tap 3 or tap 1. This guarantees that the maximum voltage across the hybrid switch BS1, BS2, will be equal to the voltage of one tap (i.e., 0.02 p.u.).

The tap-change process through the hybrid switch, when we move from the tap corresponding to NL1 to NL2 is done through a 7-step mechanism illustrated in Table 1.1, the ON condition of the switch is indicated by —11 and OFF by —01. For the position of switch M, when it is connected to BS1, it is indicated by —11, when connected to BS2 by —21 and by —01 when it is not connected.

1) wye connection with star-point floating;
2) closed-delta connection;
3) wye connection with the star point connected to line neutral (only for a three-phase four-wire system).
4) open-delta connection using two units.

The first two methods suffer from the drawback that the floating star point in wye can lead to erratic operation of the tap changer and overstress the winding insulation; while the closed-delta connection does not result in in-phase compensation and requires an extra unit compared to open-delta connection.

<table>
<thead>
<tr>
<th>STEP</th>
<th>NO LOAD SWITCHES</th>
<th>HYBRID SWITCH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NL1</td>
<td>NL2</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
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</tr>
<tr>
<td>7</td>
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</table>
Star Connection for Three-Phase Four-Wire LV Network

It is typical for the LV distribution network to have a neutral available. Thus, three single-phase OLTC transformers can be connected between the phase and neutral in grounded Y formation with the start point of the transformer connection connected to the neutral of the Figure 3.1: Y connection of the OLTC transformers to a three-phase four-wire network. Three units regulate each of the three-phase voltages independently. $\Delta V_a$, $\Delta V_b$, and $\Delta V_c$ are the series-injected compensation voltages derived from OLTC.

![Phasor diagram of series compensation in the MV (left) and LV (right) distribution network using open-delta and 31har connection, respectively. $V_x$ is the phase voltage, $V_{xy}$ is the line voltage, N is neutral, $V_{xy}$ is the line voltage, $\Delta V_x$ is the series-injected compensating phase voltage, $\Delta V_{xy}$ is the series-injected compensating line voltage where, and refers to any of the phases a,b, and c.](image)

Network as shown in Figure 3.2. The points S, SL, and L correspond to those in Figure 3.2. The compensating voltage is derived from the phase voltage and injected in/out of phase for positive and negative compensation, respectively. The main feature of the connection is that the three OLTC units can achieve independent regulation of each phase voltage. This is explained using the phasor diagram in Figure 3.2 where are the phase and line voltage at the input of the transformer and $\Delta$ are the corresponding phase and line voltage that are series injected into the grid. The phase voltage after series compensation = (12)

![Open connection of OLTC transformers to a three-phase three-wire network.](image)

Open Delta Connection for Three-Phase Three-Wire MV Network

An innovative method for controlling the line-to-line voltage in a three-wire network using only two OLTC units is through an open-delta connection, shown in Fig. 6.3. The two units are connected between phase a-b and phase c-b using phase b as the common connection point. The injected voltages $\Delta V_a$ and $\Delta V_c$ are thus derived from the line-line voltages. Direct and independent regulation of the line-line voltages $V_{ab}$ and $V_{bc}$ results, while the compensation in, that is, $\Delta V_{ac}$ is the average of ($\Delta V_{ab}$ + $\Delta V_{bc}$). During balanced operation ($\Delta V_a = \Delta V_c$), in-phase compensation of all three line-line voltages occurs and during unbalanced operation, $V_{ab}$ and $V_{bc}$ experience inphase compensation while $V_{ac}$ alone experiences a phase shift of up to 5 . The line voltage after series compensation is given by table 3.1

<table>
<thead>
<tr>
<th>LOAD VOLTAGE IN AC VOLTS</th>
<th>TRANSFORMER OUTPUT VOLTAGE IN AC VOLTS</th>
<th>RELAY STATUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RLY1</td>
<td>RLY2</td>
<td>RLY3</td>
</tr>
<tr>
<td>24.4</td>
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<td>1</td>
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<tr>
<td>22</td>
<td>21.6</td>
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<td>14.3</td>
<td>19.5</td>
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</tr>
<tr>
<td>16</td>
<td>21.2</td>
<td>0</td>
</tr>
<tr>
<td>20.8</td>
<td>20.15</td>
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</tr>
<tr>
<td>21.9</td>
<td>21</td>
<td>0</td>
</tr>
</tbody>
</table>
III. SIMULATION RESULTS

Figure 3.4: Showing the regulation of output voltage with fluctuations in supply voltage
The graph shows the regulation of output voltage with fluctuations in supply voltage. The blue line represents the load voltage in volts and the red line represents the transformer output voltage. The load voltage and the transformer output voltage shows variations as time proceeds. The table 3.1 shows the values of output current and output voltage at particular values of input voltage. When the value of output voltage increases, the value of load current also increases.

IV. CONCLUSION

Frequent voltage fluctuations and overvoltage are observed in the distribution network owing to large-scale renewable energy integration, such as PV. A novel design for a power-electronic assisted OLTC autotransformer for tackling this problem in the distribution network has been proposed. The OLTC taps were made from a combination of no-load switches and a single semiconductor-mechanical hybrid switch and exhibited several advantages.

The OLTC makes use of a mechanical switch during steady state and a semiconductor switch during tap change, resulting in the dual benefit of lower steady-state losses and no arcing during the tap change. This enables the OLTC to sustain a long lifetime when working in conditions of frequent voltage fluctuations. The OLTC can provide positive and negative compensation of the grid voltage. The use of no-load switches and the seven-step tap changing mechanism reduced the number of active switches from ten to one. The use of voltage polarity-based four-step commutation on back-to-back-connected MOSFETs provided a convenient method for performing a tap change without the occurrence of an open/short circuit and without the need for current-limiting impedance.

A single overvoltage snubber connected
V. REFERENCES


