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# 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. The paper 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 comprising of several no-load switches and a single semiconductor-mechanical hybrid switch has been proposed, that requires reduced voltage rating and 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 IGBT/MOSFET, thus achieving arc-free tap change and long lifetime of switches. The OLTC system has been customized for both LV and MV three phase distribution networks. An open-delta configuration for the MV application has been proposed that requires only two OLTC units to control all three line voltages. Simulations are carried out to verify the steady state and transient operation of the proposed OLTC.**

***Index Terms*— Distributed power generation, four step commutation, hybrid switch, on-load tap changer, series compensation, transformer, voltage fluctuations**

## I. INTRODUCTION

IN recent years, high penetration of distributed generation (DG) driven by PV panels in the distribution network has led to frequent voltage fluctuations and over-voltages [1]-[6]. Voltage control using traditional voltage regulators is unable to cope with this situation as frequent tap changes reduce the lifetime of the mechanical taps due to arcing [7]-[9]. Further, the nature of the European distribution network in general, makes voltage control through shunt compensation methods [10], [11] ineffective and expensive [34], [35]. Series compensation through centralized on-load tap changing (OLTC) distribution transformers or feeder-specific compensators is hence a suitable strategy for voltage regulation in Europe.

On-load tap changing 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 [7]-[9]. This results in lower lifetime of the switches and necessitates repeated maintenance. Nevertheless these mechanical taps have the advantage of high overload capacity and low on-state losses. On the other hand, electronic tap changers use semiconductor switches that do not have any arcing problems [7], [12]-[17]. They provide flexibility in operation but suffer from much higher steady state losses. By combining the advantages of both electronic and mechanical tap changers, power electronic assisted tap changers are obtained [18]-[22]. 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 arc-free tap changing process. 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.

This paper describes the design of a power electronic assisted OLTC autotransformer that provides voltage regulation in a European distribution network through series compensation. The novel design of the OLTC autotransformer is cost effective, efficient and has a long lifetime. Unlike earlier works that use thyristor [18]-[21], back-to-back series connected IGBTs with anti-parallel diodes are used for the two electronic switches. Voltage polarity based 4-step current commutation is used for changing between the taps which results in fast commutation without the need for current limiting impedance [7]. The OLTC has been customized for application in both MV and 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.

In the next section, the voltage fluctuation problem in the European distribution network caused due to DG is investigated in detail. In section III.A, the design of the power electronic assisted OLTC autotransformer is elaborated. Section III.B and III.C describe the construction of the hybrid mechanical-semiconductor switch and its snubber, which aids in the tap change operation. In section IV, the connection

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scheme for the proposed voltage regulator to the MV and LV distribution network is explained. The complete system is simulated in the PLECS simulation tool and the results are presented in section V.

## II. VOLTAGE FLUCTUATION AND COMPENSATION

### A. *Voltage fluctuation in distribution network*

Voltage fluctuation is a usual phenomenon that happens in the distribution grid. Traditionally power grids assume a downstream power flow that results in a voltage drop along the feeder causing under-voltage at feeder end [1]. To counteract this effect OLTC mechanism in voltage regulators and in sub-transmission transformers are used to set the voltage at the feeder head at a higher value to compensate for line drops.

However in recent years there has been a considerable increase in DG penetration in the LV distribution network mainly driven by solar and this is only expected to increase in the future [1]-[6]. This combined with heavy load insertion such as electric vehicle charging, has made voltage control more complicated [2]-[6], [23]. Large variation in DG power owing to short and long term fluctuations in wind and sunshine results in large as well as frequent variations in load voltage (up to ±10%) [2]-[5], [23], [24]. Moreover, feeders experience upstream power flow during high times of DG production causing overvoltage at feeder ends [4], [5].

For the simple case of Fig.1, the load voltage variation at feeder end can be quantified by $V_{line}$, which is the difference between the voltage at the feeder head ($\bar{E}$) and voltage at feeder end ($\bar{V}$):

$$\overline{V_{line}} = E\angle\delta - V\angle 0 = Z_s\overline{I_l} \tag{1}$$

$$\overline{S_{\text{load}}} = \overline{V}(\overline{\text{I}_\text{l}})^* = P_l + jQ_l$$

$$\overline{V_{line}} = \frac{R_sP_l + X_sQ_l}{V} + j\frac{X_sP_l - R_sQ_l}{V} \tag{2}$$

The voltage variation thus depends on the effective impedance of the line ($Z_s$=$R_s$+$jX_s$), apparent power drawn/injected by the load ($S_{load}$=$P_l$+$jQ_l$) and voltage at feeder end ($V$). The negative impacts of overvoltage, under-voltage and the large scale DG penetration have been addressed in [25], [26]. According to [25], the voltage at customer utilization point cannot exceed the tolerance level of ±10%.

In reality, the situation is much more complicated than what is shown in Fig.1 due to:

1. Non-uniform distribution of loads/DG along the feeder
2. Time varying nature of the load/DG power
3. Uneven nature of feeder length emanating from bus bar

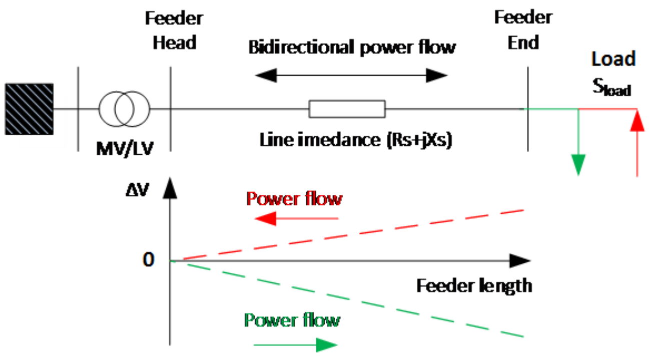


Fig. 1. Voltage drop ΔV along feeder depending on feeder length and power flow direction based on load

A comprehensive strategy is hence required for ensuring permissible voltage levels throughout the distribution network. It must compensate frequent voltage fluctuations in the form of both over-voltage and under-voltage in a cost effective and efficient manner.

### B. *Voltage regulation through OLTC transformers*

Voltage compensation can be achieved through shunt and series compensation [10], [11]:

1. Shunt compensation, where a lagging/leading current is injected into the grid to control the voltage.
2. Series compensation, where a voltage is injected in series to the existing grid voltage or a reactive element is connected in series to the line to modify line impedance.

Shunt compensation is based on the fact that injecting a leading current decreases the voltage at that point while injecting a lagging current increases the voltage. It can be seen from (1) that the reactive power $jQ_l$ has a direct correlation to the voltage drop along the line. Examples of shunt compensation are mechanically switched capacitor/inductor banks, thyristor-controlled reactor (TCR) and thyristor-switched capacitor (TSC) that act as a variable current source. Series compensation on the other hand works on the basis of injecting a series voltage that compensates for the voltage drop along the line $V_{line}$. Examples are self-commutated switch based FACTS devices like Unified Power Flow Controller (UPFC), on-load and off-load tap changing transformers.

The nature of the European distribution network is generally characterized by feeders that can reach four to five times the length of those in North America and are predominantly underground cable networks with high *R/X* ratio [23], [27]. In German LV grids, *R/X* values of 2 are typical for overhead lines and *R/X* values of 2.5 are typical for cable networks [27]. This means that the voltage variation in the European grid is much higher than in the North American grid. More importantly shunt compensation is less effective due to the high *R/X* ratio [3], [34], [35] resulting in increased reactive current flows and line losses. This can be explained using equation (2), which can be approximated as [10]:

$$V_{line} = \frac{R_sP_l + X_sQ_l}{V} \tag{3}$$

Then the reactive power ΔQ that has to be injected/absorbed to compensate the voltage fluctuation ΔV along the line due to change in load power ΔP can be given as:

$$\Delta V = \frac{R_s(\Delta P) + X_s(\Delta Q)}{V} = 0 \qquad \Delta Q = -\frac{R_s}{X_s}\Delta P \tag{4}$$

It can be seen from (4) that for networks with higher R/X ratio, more reactive power is required to compensate for voltage variations. One feasible solution for Europe is hence through series compensation using tap changing transformers.

Tap changing transformers are a widely used technique for voltage control in the distribution network [4], [5], [7-9]. By changing of the transformer taps, the voltage ratio of the

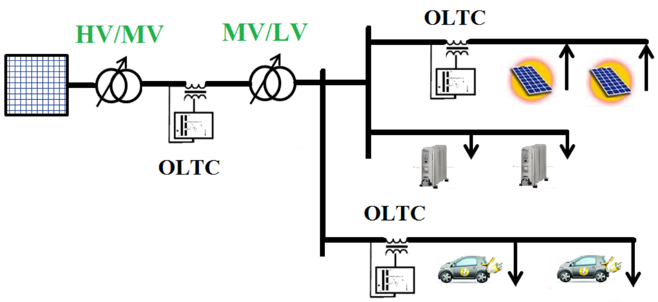


Fig. 2. Connection of OLTC transformer to feeders in MV and LV network that have long length and/or high PV penetration and loading like EV

transformer windings is modified resulting in a variable output voltage for a fixed input voltage. Off-load tap changing mechanisms are present on distribution transformers but they cannot be operated without interrupting the supply. On the other hand, conventional voltage regulators and OLTC sub-transmission transformer use mechanical switches that can be operated on-load.

For ensuring uninterrupted electricity supply in future distribution network with large injection of DG power, it is necessary that tap changers are able to change taps on-load. This can be implemented in two ways. One method is by centralized compensation through OLTC distribution transformers, where all feeders emanating from the distribution transformer have the same amount of compensation. This method is cost effective compared to the second technique, but it fails in networks with non-uniform distribution of DG and/or with uneven feeder lengths. This is because it provides equal compensation for all feeders irrespective of the loading or DG power injection. Further, if there are long feeders with large DG, compensating for over-voltage for customers located at the end of the feeder will result in under-voltage for customer close to the feeder head.

The second method is through feeder specific decentralized compensation where an OLTC transformer is connected to those hot spot feeders that have high PV generation and/or long length. The focus of this paper will be on the design of such a feeder specific OLTC transformer. It is especially suitable for networks with non-uniform distribution of DG, loads and uneven feeder lengths; which are often encountered in a European scenario. Fig.2 shows different possibilities of connecting such a device to the MV/LV distribution network. The OLTC unit is specifically connected to those feeders that have long length and/or high PV penetration.

## III. DESIGN OF THE PROPOSED OLTC AUTOTRANSFORMER

### *A. OLTC design using no-load switch & hybrid switch*

Eleven different OLTC topologies using conventional two-winding transformers and autotransformer were compared in [28] on the basis of the voltage and current ratings of the transformer and tap switches and isolation requirements. The OLTC topology shown in Fig.3 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.

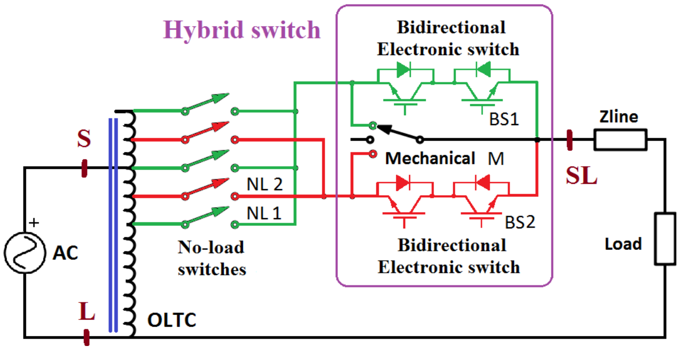


Fig. 3. OLTC autotransformer using no-load switches (NL1, NL2) and hybrid switch made of two electronic switches BS1,BS2 and a mechanical switch M

The use of an autotransformer saves on material and cost, and the throughput power is approximately ten times the transformed power [29]. The autotransformer turn ratio of input to output is 10:11. If the rated input voltage is 1p.u. then the taps are present on the section of windings from 0.9p.u. to 1.1p.u. Ten taps are present each of 0.02p.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 [7]-[9] shown in Fig.4. 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.

In Fig.3, 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 & 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 M 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 OFF condition is 0.2p.u.

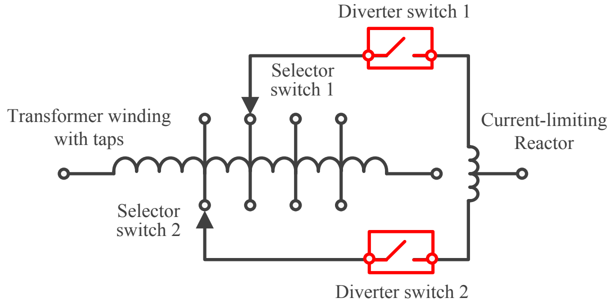


Fig. 4. Diverter switch type voltage regulator using no-load ‘selector’ switch [6]. Only two ‘diverter’ switches are required regardless of number of taps

TABLE I
7 STEP COMMUTATION BETWEEN TAPS

| **Step** | **No load switch** | | **Hybrid switch** | | |
|---|---|---|---|---|---|
| | **NL 1** | **NL 2** | **BS 1** | **M** | **BS 2** |
| **0** | 1 | 0 | 0 | 1 | 0 |
| **1** | 1 | 1 | 0 | 1 | 0 |
| **2** | 1 | 1 | 1 | 1 | 0 |
| **3** | 1 | 1 | 1 | 0 | 0 |
| **4** | 1 | 1 | 0 | 0 | 1 |
| **5** | 1 | 1 | 0 | 2 | 1 |
| **6** | 1 | 1 | 0 | 2 | 0 |
| **7** | 0 | 1 | 0 | 2 | 0 |

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, M will be equal to the voltage of one tap i.e. 0.02p.u.

The tap change process through the hybrid switch, when we move from tap corresponding to NL1 to NL2 is done through a 7-step mechanism illustrated in Table 1. In Table 1, ON condition of switch is indicated by ‘1’ and OFF by ‘0’. For the position of switch M - when it is connected to BS1, it is indicated by ‘1’, when connected to BS2 by ‘2’ and by ‘0’ when not connected.

In step 1, M and NL1 carries the load current and the no-load switch corresponding to the new tap position, NL2 is turned ON. In steps 2 and 3, BS1 is turned ON and the current commutates from BS1 to M without an arc occurring in M. In step 4, commutation of current happens between the two semiconductor switches BS1 and BS2. In steps 5 and 6, the current is transferred from BS2 back to M. It is ensured throughout that the change of state of no-load switches (NL1 or NL2) always happens when the series connected electronic switch (BS1 or BS2) is in OFF condition.

The OLTC system is customized for application in MV and LV distribution network and Table 2 shows the corresponding parameters. The no-load switches are rated for 1p.u. nominal load current and 0.2p.u. voltage. The hybrid switch (M, BS1, BS2) is rated for 0.02p.u. voltage and 1p.u. current. The simple operation of no-load switches and small voltage ratings of the electronic switches results in low overall cost of OLTC.

A vital aspect of the design is its modular nature. Modifying the total regulation range to ±15% or ±5%, or changing the voltage per tap to 1.5% or 3%, can be realized by simply adding/reducing the number of no-load switches and still using only a single hybrid switch. It should be realized that the cost of no-load switches does not increase with increased voltage ratings unlike semiconductor switches. The novel power electronic assisted OLTC design can be implemented on existing voltage regulators like in [17].

TABLE II
PARAMETERS OF THE MV AND LV OLTC SYSTEM

| **Parameter** | **MV** | **LV** |
|---|---|---|
| Voltage level (line-line, rms) | 20 kV | 400 V |
| Maximum rated load current (rms) | 577A | 577A |
| Neutral available | No | Yes |
| Connection scheme | Open delta | Wye |
| 1-phase OLTC units required | 2 | 3 |
| Autotransformer transformed power | 1.15 MVA | 13.3 kVA |
| Autotransformer throughput power | 12.65 MVA | 146.3 kVA |
| Percentage impedance | 2.5% | 6% |
| Bidirectional electronic switch | IGBT | MOSFET |

## *B. Bidirectional semiconductor switch for hybrid tap changer*

The semiconductor switch BS1 and BS2 used in the hybrid switch must be bidirectional - block both positive and negative voltages when OFF and conduct current of both directions when ON. Several possibilities exist for realizing such a bidirectional switch as discussed in [7]. In this design, series connection of two back-to-back IGBTs (having an anti-parallel diode in common emitter configuration) or MOSFETs are used for switch BS1 and BS2 for MV and LV scenario. The choice is driven by the fact that commutation of current between BS1 and BS2 (Step 4 of 7-step tap change method) can be done without the occurrence of a short/open circuit through voltage polarity based 4-step current commutation when using IGBT/MOSFET [13], [14], [30]-[32]. Thyristor is not the preferred choice because of the inability to control the switch turn off, the *di/dt* limitations and the need for current limiting impedance during tap change. Further for the required low voltage rating of switches, MOSFET/IGBT are widely available in the market than thyristor.

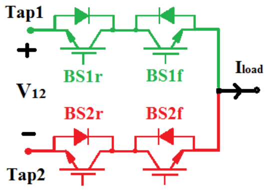
Table 3 and Fig.5 explain the firing sequence for the forward (BS1f, BS2f) and reverse (BS1r, BS2r) conducting IGBTs when the voltage across the hybrid switch $V_{12}$ is positive:

1. BS1f and BS2r are not simultaneously turned ON when $V_{12}>0$ and BS1r and BS2f are not ON at the same time when $V_{12}<0$, thus preventing a short circuit.
2. One forward conducting and one reverse conducting IGBT is always ON to carry the AC load current

A similar sequence can be used when $V_{12}<0$ as described in [7], [14], [30]-[32]. It takes up to 8µs to commutate between the switches depending on the switch type, transformer

TABLE III
4-STEP CURRENT COMMUTATION BETWEEN BS1 AND BS2 WHEN $V_{12}>0$

| **Step** | **BS1f** | **BS1r** | **BS2f** | **BS2r** |
|---|---|---|---|---|
| **0** | 1 | 1 | 0 | 0 |
| **1** | 1 | 1 | 1 | 0 |
| **2** | 0 | 1 | 1 | 0 |
| **3** | 0 | 1 | 1 | 1 |
| **4** | 0 | 0 | 1 | 1 |



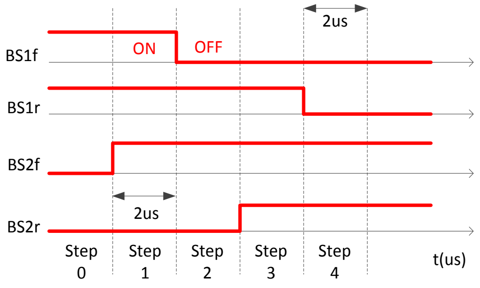


Fig. 5. Timing sequence of gate signals to electronic switches BS1 and BS2 during 4-step commutation when $V_{12}>0$ and each step is of 2us duration.

leakage inductance, snubber capacitance and load current. The technique requires no current limiting impedance which is a major advantage over conventional voltage regulators [7]-[9]. Voltage polarity based commutation is preferred over the current polarity based commutation because of lower failure hazard. In the latter case, an erroneous current polarity judgment which typically occurs around the zero crossing of the current, will cause an open circuit condition. This subsequently results in a large overvoltage across the switches given by *L(di/dt)*, where *L* corresponds to the effective line inductance and *(di/dt)* is the slope of the current turn off transient. On the other hand for the voltage polarity method, an error in polarity judgment around the zero crossing of voltage will lead to a short circuit of the tap. The failure is however less hazardous due to the small voltage available around the zero crossing for driving the short circuit current.

For the LV OLTC, the electronic switch has to be rated for 577A current and 8V blocking capacity based on the nominal power rating of the transformer and the maximum voltage between two consecutive taps. Since commercially available MOSFET are more economical than IGBT for such ratings, back to back series connected MOSFETs will be used for the LV scenario. The MOSFET body diode replaces the anti-parallel diode used in the case of IGBT.

The total time for the 7-step commutation is determined by the time taken for the operation of no-load switches and the mechanical switch M of hybrid switch (Step 1,3,5,7), as the semiconductor switches operate in 8µs. It is estimated that it would take up to 200ms to change a tap considering 50ms for each operation of mechanical/no-load switch.

### *C. Overvoltage snubber for hybrid switch*

During a change of tap, the current through the transformer tap leakage inductance is interrupted in step 4, leading to an overvoltage [7], [15]. Fig.6 can be used to analyse this effect where the schematic of two taps of an OLTC are shown. $V_{tap}$, $L_{leak}$, $R_{leak}$ are the voltage, the leakage inductance and winding resistance of one tap, with the load modelled as a current source. Initially let BS1 be ON, so the voltage at *C* is ($V_1+V_{tap}$). Now a tap change is made from BS1 to BS2 so that the load voltage at point *C* is $V_1$. During this process, let BS1 interrupt the load current with a slope $\alpha=(di/dt)$ as the current commutates to switch BS2, then a overvoltage is experienced by the turning-off switch BS1 due to the tap leakage inductance given by

$$V_{BS1} = V_{tap} + L_{leak}\left(\frac{di}{dt}\right) \qquad (5)$$

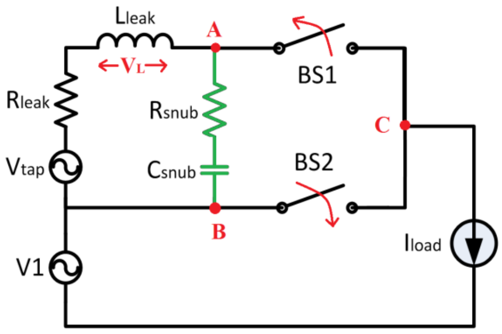


Fig. 6. Overvoltage snubber ($R_{snub}$, $C_{snub}$) connected across the electronic switches BS1 and BS2 to prevent overvoltage during changing of taps due to the leakage inductance $L_{leak}$ of the transformer windings. $R_{leak}$ – Tap winding resistance, $V_{tap}$ – voltage of one tap, *V1*-Voltage of transformer secondary

Thus a large overvoltage will be experienced by the switch depending on the leakage inductance of the tap and the current being turned off. Damped LC oscillations will be observed due to the small but finite value of tap capacitance and a damping due to the resistance of the tap windings. This overvoltage can be very high and can permanently damage the switch.

This calls for the need for using an overvoltage snubber to protect the switches. Alternatively, if the tap change is done close to zero current, then there will be minimum overvoltage effect as given by (7). A RC overvoltage snubber ($R_{snub}$, $C_{snub}$ in Fig.6) can be used across the switches [7] as shown. This results in the energy stored in the inductor to be exchanged with the snubber capacitor resulting in LC oscillations. If we neglect the damping due to $R_{leak}$ and $R_{snub}$, we can write:

$$\text{If } I_{load}\big|_{step4} = I_1, \quad \frac{1}{2}L_{leak}(I_1)^2 = \frac{1}{2}C_{snub}(\Delta V)^2 \qquad (6)$$

$$\Delta V = I_1\sqrt{L_{leak}/C_{snub}} \qquad (7)$$

$$V_{BS1} = V_{tap}\big|_{step4} + I_1\sqrt{L_{leak}/C_{snub}} \qquad (8)$$

$$f_{osc} = 1/(2\pi\sqrt{L_{leak}C_{snub}}) \qquad (9)$$

The higher the value of $C_{snub}$ and the lower the value of $L_{leak}$, the lower the overvoltage on the switch. $R_{snub}$ is designed mainly to limit the capacitor discharge current at switch turn ON and to damp the LC oscillations. In this design, a RC snubber of 100µF and 0.01Ω was used.

## IV. CONNECTION SCHEME FOR THREE PHASE NETWORK

In this section, different possible connection schemes for a single phase OLTC transformers to a three phase distribution network is examined. Based on the general nature of European distribution network, the following assumptions are made in the design of the connection scheme:

1. MV distribution network – three-phase three-wire network where line-line voltage has to be regulated. Unbalanced loading of phases is not an issue, therefore independent regulation of phases is not required.
2. LV distribution network – three-phase four-wire network with neutral present, where phase voltage has to be regulated. Unbalanced loading of phases is prevalent, therefore independent regulation of each phase is required.

Two/three single phase OLTC can be connected to a three phase network in 4 ways [8], [33]:

1. Wye connection with star point floating
2. Closed-delta connection
3. Wye connection with star point connected to line neutral (only for 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 [8].

### A. *Y connection for 3-phase 4-wire LV network*

It is typical for LV European 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 network [8], [33] as shown in Fig.7. The points *S, SL* and *L* correspond to those in Fig.3. 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 Fig.8, where $V_x$, $V_{xy}$ are the phase and line voltage at the input of the transformer and $\Delta V_x$, $\Delta V_{xy}$ are the corresponding phase and line voltage that are series injected into the grid. The phase voltage $V_x$*'* after series compensation:

$$\overline{V_x^{'}} = \overline{V_x} + \overline{\Delta V_x} \tag{10}$$

### B. *Open delta connection for 3-phase 3-wire MV network*

An innovative method for controlling the line-line voltage in a three wire network using only two OLTC units is through an open-delta connection, shown in Fig.9. The two units are connected between phase a-b and phase c-b using phase b as the common connection point [8], [33]. 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 $V_{ac}$ i.e. $\Delta V_{ac}$ 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 in-phase compensation while $V_{ac}$ alone experiences a phase shift of upto 5˚. The phasor diagram is shown in Fig.8. The line voltage $V_{xy}$*'* after series compensation is given by:

$$\overline{V_{xy}^{'}} = \overline{V_{xy}} + \overline{\Delta V_{xy}} \tag{11}$$

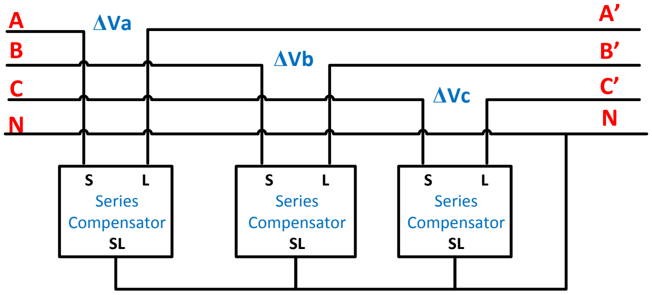


Fig. 7. Y connection of OLTC transformers to a 3-phase 4-wire network. Three units regulate each of the three phase voltages independently. ΔVa, ΔVa, ΔVc are the series injected compensation voltages derived from OLTC

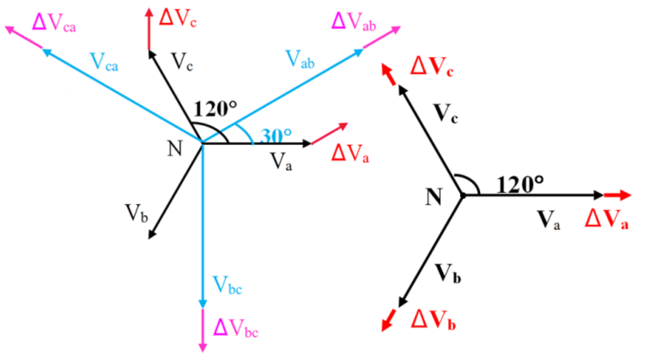


Fig. 8. Phasor diagram of series compensation in MV (left) and LV (right) distribution network using open-delta and Y connection respectively.
$V_x$– Phase voltage, $V_{xy}$ –Line voltage, *N*-Neutral, $V_{xy}$– Line voltage, $\Delta V_x$- Series injected compensating phase voltage, $\Delta V_{xy}$- Series injected compensating line voltage where x, y refers to any of the phases a, b, c

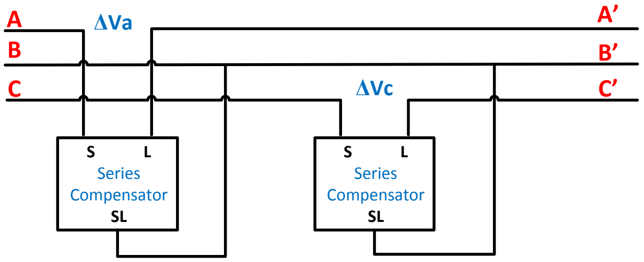


Fig. 9. Open Δ connection of OLTC transformers to 3-phase 3-wire network

## V. SIMULATION OF PROPOSED OLTC SYSTEM

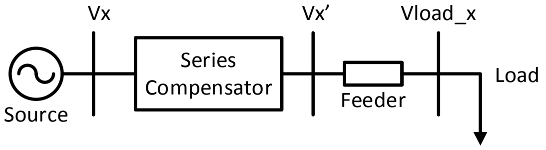


Fig. 10. Single line diagram of OLTC system that was used in simulation

The MV and LV 3-phase OLTC system was modeled based on the single line diagram shown in Fig.10. The feeder (line/cable) was modeled as a series connection of two T-sections. The load for the MV scenario was a delta connected impedance drawing nominal current at power factors ranging between 0.8 lagging to 0.8 leading, while a similar Y connected load was used for the LV case. The standard PLECS model for IGBT and MOSFET was used in the simulation. The time step for 4-step commutation was 2µs.

Steady state and transient operation of the system was investigated and the waveforms are shown in Fig. 11.1 to 11.7. Fig. 11.1 and 11.2 shows voltages at the input and output of the OLTC for the MV and LV scenario depicting the independent regulation of phases. In Fig 11.3, DG reverse power flow was modeled using a negative current source in phase A and the voltage at the OLTC output is set to be lower than the OLTC input. The corresponding overvoltage at load end is hence compensated by the OLTC. The transients occurring during tap change and the impact of the snubber capacitance and current at commutation instant (as described by (6) - (9)) can be examined through the waveforms in Fig. 11.4-11.7. The current at the commutation instant has a direct correlation on the magnitude of the LC oscillations when it increases from 60A to 600A, as seen in Fig. 11.4 and Fig.11.5.

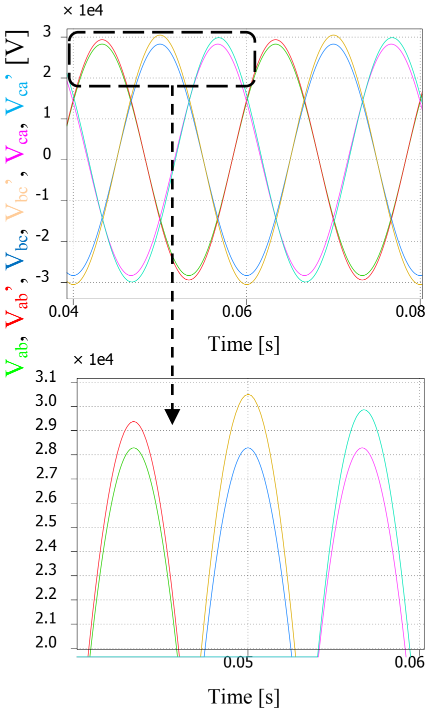


Fig. 11.1 - Steady state line voltages [V] at input $V_{xy}$ and output $V_{xy}$' of OLTC as a function of time [s] for MV scenario. The two OLTC units are set for 4% and 8% positive compensation respectively, resulting in 6% compensation in third line voltage.

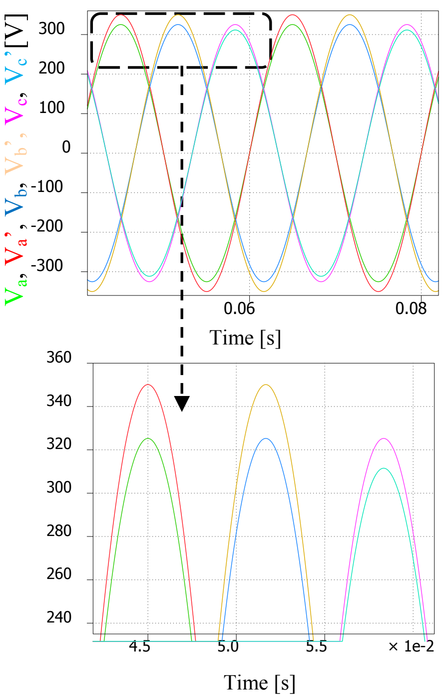


Fig. 11.2 - Steady state phase voltages [V] at input $V_x$ and output $V_x$' of OLTC as a function of time[s] for LV case. The three OLTC units are regulated separately and set for 8%, 6% and -2% compensation.

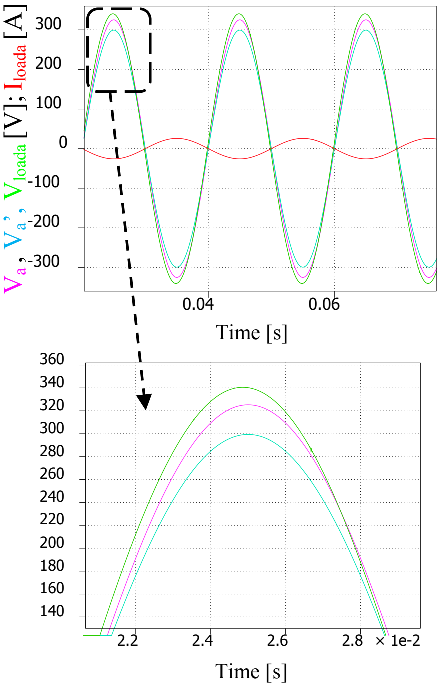


Fig. 11.3 - Steady state phase voltages [V] at input $V_x$ and output $V_x$' of OLTC as a function of time[s]. An active DG is connected at the load end of the LV OLTC system which is set to -8% compensation

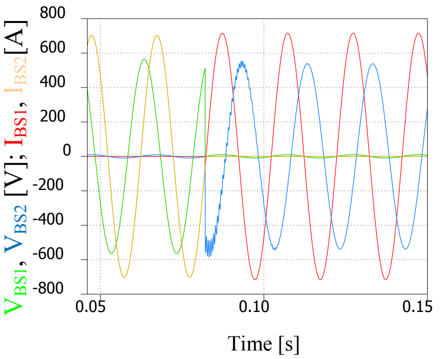


Fig. 11.4 – Transient voltage $V_{BS1}$, $V_{BS2}$ and current $I_{BS1}$, $I_{BS2}$ of the two IGBT of bidirectional switch M during 4-step commutation from BS2 to BS1, when load current at commutation instant is 60A and snubber capacitance is 100 µF (for MV scenario)

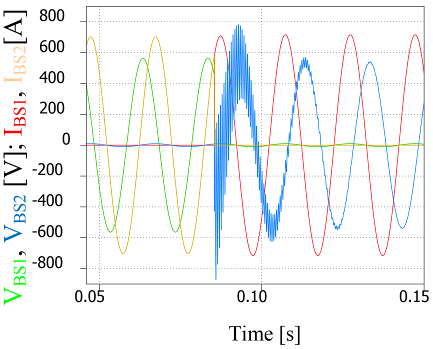


Fig. 11.5 – Transient voltage $V_{BS1}$, $V_{BS2}$ and current $I_{BS1}$, $I_{BS2}$ of the two IGBT of bidirectional switch M during 4-step commutation from BS2 to BS1, when load current at commutation instant is 600A and snubber capacitance is 100 µF (for MV scenario). Larger magnitude of LC oscillations occur due to larger energy stored in the tap leakage inductance compared to Fig. 11.4 .

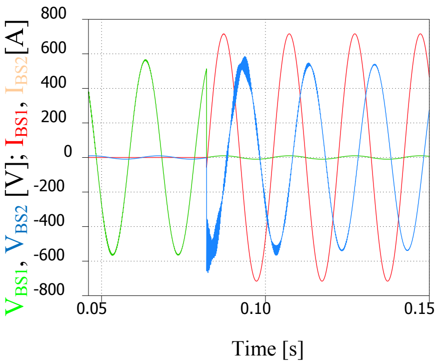


Fig. 11.6 - Transient voltage VBS1, VBS2 [V] and current IBS1, IBS2 [A] of the two IGBT of the bidirectional switch M during 4-step commutation from BS2 to BS1, when current at commutation instant is 60A and snubber capacitance is 10 µF. Larger magnitude of LC oscillations occur due to smaller snubber capacitance compared to Fig. 11.4. Overvoltage on switch BS2 crosses 600V.

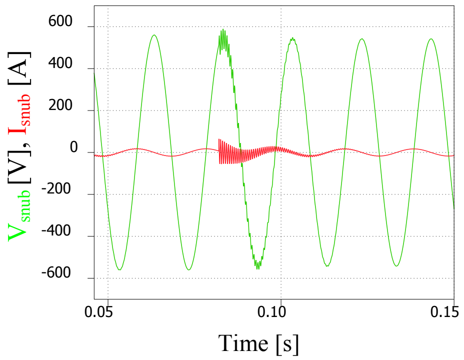


Fig 11.7 - Transient voltage $V_{snub}$ [V] and current $I_{snub}$[A] of snubber capacitor during 4-step commutation from BS2 to BS1 in MV OLTC, depicting the LC oscillation between leakage impedance and snubber capacitance of 100 µF for the scenario depicted in Fig. 11.4

In Fig.11.5 and Fig.11.6, a lower snubber capacitance of 10µF compared to the nominal value of 100µF leads to high frequency oscillations of large amplitude. From the figures, it can be concluded that the commutation of the semiconductor switches must be performed close to current zero and the optimal value of snubber capacitance should be chosen to limit the LC oscillations to lower amplitude.

## VI. CONCLUSIONS

Frequent voltage fluctuations and overvoltage are observed in the distribution network owing to large scale renewable energy integration like PV. A novel design for a power electronic assisted OLTC autotransformer for tackling this problem in the European 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 both positive and negative compensation of the grid voltage. The use of no-load switches and the 7-step tap changing mechanism reduced the number of active switches from ten to one. The operation mechanism of changing one tap at a time of 0.02p.u. voltage reduced the voltage ratings of switches by ten times, from 20% of grid voltage in conventional tap changers to 2% in the current design.

The use of voltage polarity based 4-step commutation on back to back connected IGBT/MOSFET provided a convenient method for performing a tap change without the occurrence of an open/short circuit and without the need for a current-limiting impedance. Commutation of current between the semiconductor switches occurred in less than 8 µs as verified in simulation.

A single overvoltage snubber connected across the hybrid switch protects the switches from overvoltage resulting from interruption of current through the tap leakage inductance. Damped LC oscillation between the leakage inductance and snubber capacitance were observed in simulation and last for 40-60ms. Optimal value of snubber capacitor and commutation close to the zero crossing of the load current are vital to protect the semiconductor switches from transient overvoltages.

The OLTC has been customized for application in both LV and MV distribution network. Open-delta connection using two OLTC units and Y connection using three OLTC units have been found to be most suitable for control of line voltages in MV network and phase voltages in LV network respectively.

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