Transient Characteristics of On-load Tap Changers During Change-over Operation

Abolfazl Babaei, Waldemar Ziomek, Aniruddha M.Gole

Abstract-- **This paper presents the transient behavior of the On-Load Tap Changing (OLTC) transformers during change-over operation. A model is developed for the change-over process capable of simulating the recovery voltage across the change-over selector and the switch current. The model is verified by comparing its results in the steady state with theoretical phasor analysis-based calculation. The effect of adding tie-in resistors with the selector switch is investigated with the proposed model.**

Keywords: **OLTC, change-over selector transient, Recovery voltages, Switch Current, transient model.**

I. INTRODUCTION

On-load tap-changers (OLTCs) are the electro-mechanical switching equipment operating within power transformers, allowing to change the output voltage by changing the tap position under load. The operation of OLTCs corresponds to a sequence of switching events within defined timing intervals. The main goal of these switching operations is to compensate over and under voltages stemming from load variations [1]. The high-reliability operation of power transformers is crucial, as it can reduce the number of power outages and cost associated with maintenance. Typically, one of the most expensive and vulnerable parts of transformers are OLTCs with the majority of power transformer failures occurring due to a defect in its windings [2-3]. The winding failures can be mechanical in origin, initiated by a current surge that causes the winding structure to deform. However, the transients related to OLTC tap changing are not so critical, as modern tap changers use vacuum interrupter technology. When the vacuum interrupter opens while changing the taps, the created arc is fully contained in the vacuum chamber and does not contaminate the oil with the products that result from an arc in the oil. So far, existing research has proposed ways to decrease the adverse effects of surge currents and voltages on the OLTCs. For example, publications [4-7], discuss optimized switching so that the switching from one tap to another does not create a break in a circuit which has an inductive characteristic. Acoustic signals and empirical mode decomposition algorithm have also been employed to determine the switching state of the mechanical tap changer. These methods are sufficiently fast to enable the protection unit to avoid any long-time circulating current and open-circuit voltages. In [8], solid-state switches as thyristors were used in tap changer transformer to change the position of the tap. Although the paper did not consider the transient response of change-over selector during the change-over time, the authors state that the proposed design could decrease the arc to a large extent, which reduces the maintenance cost.

Tap changing transformers may include a “change-over” switch which permits the tap changing winding portion to be inserted with either positive or negative polarity so that the tap voltage can add or subtract from the main winding voltage as in Fig. 1 a. The change-over switch is always operated in the zero-voltage position (tap A_0), so that its operation does not create a voltage magnitude change. Once in this position, the OLTC taps are increased to increase (or decrease) the output voltage.

The earlier literature discusses the management of potential issues related to OLTC operation, but does not consider the effects of transients due to the change-over switch operation, due to the belief that the operation of the change-over switch is always done at zero tap position and the output voltage does not change when it is operated. However, there is a transient associated with the change-over switch, as its operation discharges parasitic capacitance across the winding as shown in Fig. 1b. This paper investigates this transient. In fact, the change-over switch in Fig. 1 a is not instantaneously moved from the “+” to the “-” position, but is maintained in the electrically floating condition, so that any arc associated with the capacitive discharge can be effective.

This paper provides a model for the transient behavior of the change-over selector by considering two factors – namely the recovery voltages and the magnitude of the currents in the contacts. After transferring the current, the gap between the contacts stressed during the change over must be capable of withstanding the recovery voltage and switch currents.

In this paper, a mathematical model for the change-over operation is developed, and the recovery voltages and switch

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currents are investigated in section II. Section III shows the arc characteristics used in this paper. Then, a model to simulate the transient characteristics of change-over selector is presented. Section V demonstrates the simulation results of the recovery voltages and the switch currents. The effect of the tie-in resistor will be modelled and investigated in section VI. In section VII, the conclusion will be provided.

II. RECOVERY VOLTAGES AND SWITCH CURRENTS

The tap winding is galvanically isolated from the main winding by the change-over selector during the transition from the "+" contact to the "–" contact, when the tap winding is electrically floating. Then, a recovery voltage V_{R+} exists between the stationary contact (+) and Tap_A0 resulting from the potential of the adjacent windings and winding coupling capacitances as shown in Fig.1. b. Similarly, V_{R-} when change-over selector switches from "-" to the "+" contact. Note that the current I_{Switch}, interrupted during this change-over is capacitive and depends on the coupling capacitances of the tapped winding [12].

Fig.1. (a) shows a three-phase delta-connected OLTC structure with the change-over selector. Fig.1. (b) shows one phase of the studied winding. Although the actual capacitance is distributed, for simplifying the mathematical model, lumped capacitors are used. Thus, C_1 is the capacitance of the tap winding (measured from central coil of each winding) to the adjacent winding, and C_2 is the capacitor to ground. V_{R+} is the voltage of the stationary contact (+) with respect to Tap_A0. Likewise, V_{R-} is the voltage of the stationary contact (-). Also, U_1 and U_2 represent the voltage of the adjacent winding.

As shown in Fig.1 (b), the change-over switch is always operated in the zero-voltage position (tap A_0), so that its operation does not create a voltage magnitude change, whether changing from "+" to "–" or from "–" to "+".

In [12], it is shown that the recovery voltages and switch currents can be calculated by using the equivalent circuit shown in Fig. 2. The voltage V_Y represents the voltage (w.r.t. ground) of the change-over selector contact "0", which is connected to the end of the HV winding. Although the switching is a transient process, a relatively good idea of the recovery voltage and switch current can still be obtained from a phasor calculation [12]. From Fig. 2 (a) and phasor analysis, V_Y is as in (1).

$$V_Y = \frac{-V_{HV}}{2} + \mathrm{j}\frac{V_{HV}}{2\sqrt{3}} \tag{1}$$

Change-over selector moving from position "+" to "-" gives different results for the recovery voltages and switch currents compared to the results for moving from "-" to "+". The reason is that the value of the voltage across capacitor C_2 is different for V_{R+} and V_{R-}. This is because of the sign of $\frac{V_{Tap}}{2}$ which is positive when determining V_{R+} and negative for V_{R-} as shown in Fig. 2. b. Likewise, for the switch currents.

The value of the recovery voltage can be calculated by the equations (2) and (3) [12], where V_{R+} and V_{R-} are the values of recovery voltage when transitioning from "+" to "–" and from "–" to "+", respectively.

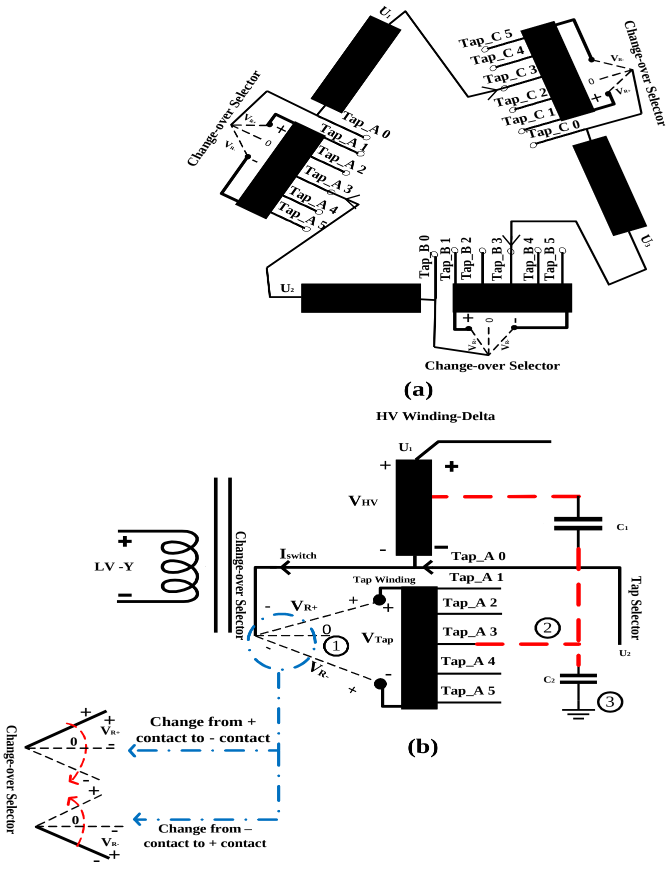


Fig. 1. The winding arrangement of the studied transformer (a) Three-phase structure (b) one-phase structure [12].

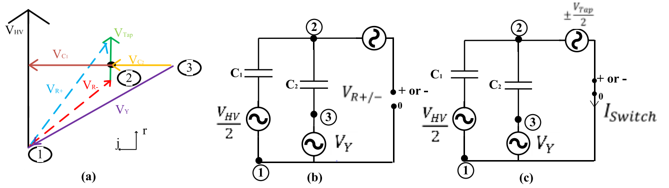


Fig. 2. (a) The phasor diagram, (b) the equivalent circuit to calculate the recovery voltage (b) the equivalent circuit to calculate the Switch currents [12].

$$|V_{R+}| = \sqrt{2} \times \left[\sqrt{\left(\frac{V_{HV}}{2} + \frac{V_{Tap}}{2}\right)^2 + \left(\frac{V_{HV}}{2\sqrt{3}} \times \frac{C_2}{C_1 + C_2}\right)^2}\right] \tag{2}$$

$$|V_{R-}| = \sqrt{2} \times \left[\sqrt{\left(\frac{V_{HV}}{2} - \frac{V_{Tap}}{2}\right)^2 + \left(\frac{V_{HV}}{2\sqrt{3}} \times \frac{C_2}{C_1 + C_2}\right)^2}\right] \tag{3}$$

V_{HV} is the voltage of the HV winding, I_F is the forward current, and V_{Tap} is the voltage across the tap winding.

According to Fig. 2. b, the peak value of the switch current for the "+" contact is shown in (4), and its peak value for "-" contact can be found by employing (5) [12].

$$\begin{aligned} &|I_{Switch}| \\ &= \sqrt{2} \\ &\times \left[\omega \times \sqrt{\left(\frac{V_{HV}}{2\sqrt{3}} \times C_2\right)^2 + \left(\left(\frac{V_{HV} + V_{tap}}{2} \times (C_1 + C_2)\right)\right)^2}\right] \end{aligned} \tag{4}$$

$$|I_{Switch}| = \sqrt{2} \times \left[\omega \times \sqrt{\left(\frac{V_{HV}}{2\sqrt{3}} \times C_2\right)^2 + \left(\left(\frac{V_{HV} - V_{tap}}{2} \times (C_1 + C_2)\right)\right)^2} \right] \quad (5)$$

where ω is the angular frequency.

III. ARC CHARACTERISTICS

In literature, Mayr's [10] and Cassie's [11] models are two widely used models for arcs with non-linear electric conductance, where instantaneous arc conductance is a function of power. Mayr's model which is better for simulating a low current arc (as is the case for the change-over selector in oil), is used in this paper. The Mayr arc model behaves as a non-linear conductance, and it is described by the equation (6) [9].

$$\frac{d\ln(g)}{dt} = \frac{1}{\tau} \times \left(\frac{\mathrm{u_{arc}} \times i_{arc}}{\mathrm{P}} - 1\right) \quad (6)$$

Where g is the instantaneous conductance value, τ represents the Mayr's time constant, $\mathrm{u_{arc}}$ is the arc voltage, $\mathrm{i_{arc}}$ represents the arc current, and P is the cooling power.

To simulate the breaker with arc, Mayr's model block in the MATLAB Simulink is employed [9]. This block considers a constant value for τ and cooling power, P. In this paper, the default values for these two parameters are considered which are $\tau = 0.3 \times 10^{-6}$ and $P = 30900\ W$[9]. Fig. 3. shows the Mayr's control block in MATLAB Simulink.

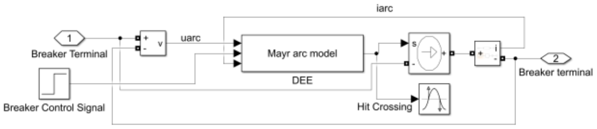


Fig. 3. The breaker with the Mayr's arc model in MATLAB Simulink [9].

As shown in Fig. 3, the breaker control signal is employed to control the contact separation of the breaker. A voltage of the control signal is from a value zero to one at the determined contact separation time. When the contacts are closed, the differential equation shown in (7) is solved [9].

$$\frac{d\ln(g)}{dt} = 0 \quad (7)$$

Therefore, the arc model behaves as a conductance with the value $g(0)$ which corresponds to a short circuit. In the MATLAB Simulink simulation g(0) = 10^4 S (or 0.0001Ω). Then, beginning from the contact separation time, the Mayr arc model equation shown in (6) is incorporated by using the Simulink DEE (Differential Equation Editor) block. Also, the output of the Mayr arc model is a current determined from "uarc" and g(t), which is injected at the breaker terminal.

IV. PROPOSED TRANSIENT MODEL OF CHANGE-OVER PROCESS

The model used to investigate the transient characteristic of the OLTC's change-over selector operation is shown in Fig. 4. As one may see in this figure, the primary winding (LV) is star-connected, and the secondary winding (HV) is delta-connected. The tap winding is delta-connected. Also, the effects of coupling capacitances, represented by the capacitors, C_1 and C_2, are considered in the model. To model the change-over process, two fictitious breakers, Breaker 1 and Breaker 2, are implemented as shown in Fig. 4. If the Breaker1 is activated, it means that the change-over selector is initially connected to "+" contact. Likewise, if the Breaker2 is on, the change-over selector is initially connected to the "-" contact. When moving "+" to "-" VR+ is initially 0, and its value indicates the recovery voltage across the selector as it is moving to the "-" contact. Likewise, for VR- when moving from "-" to "+".

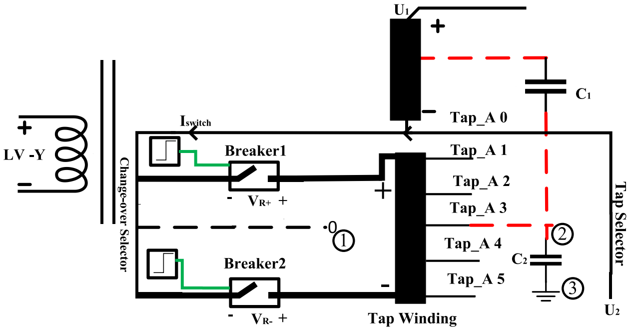


Fig. 4. The arrangement of the proposed model.

V. SIMULATION AND CALCULATION RESULTS

The proposed circuit with the arc model was simulated in MATLAB Simulink software with transformer parameters as shown in Table I. The duration of the simulation is one second. In order to continue an additive connection of the tap winding to the HV winding, the change-over selector is connected to the "+" contact for the first 0.4 seconds of simulation, and so Breaker1 is in the on state. During this time, the voltage across the "+" contact, V_{R+}, will be zero as the structure shown in Fig.5. (a). Exactly at 0.4 seconds into the simulation, the change-over selector starts to move to the - contact, and two stationary contacts (+ and -) which are connected to the tap winding are electrically floating for 200 ms during this time, as it is shown in Fig.5. (b). This causes a change in the value of V_{R+} and V_{R-}, This change in the voltages represents the value of recovery voltage, and could be significantly larger than the steady-state voltage across the change-over selector contacts. It should be noted, that at the beginning of the movement of the change-over selector, there are re-strikes between moving contact and stationary contact (+) due to the coupling capacitances and adjacent winding voltages, while at the end of the motion, there may be pre-strikes from a moving contact approaching the stationary contact "-". The processes of moving the change over-selector is shown in Fig.5.

TABLE I
TRANSFORMER PARAMETERS

Transformer MVA rating (nominal tap)	100 MVA
Magnetization Resistance (R_m)	$1.3824\times 10^5\ \Omega$
Magnetization Inductance (L_m)	366.69 H
HV winding Voltage	230 kV (Delta)
LV winding Voltage	13.8 kV (Y)
C_1	10 nF
C_2	3 nF
Tap winding	15% of HV winding
Change-over time	200 ms

A. *Changeover from "+" to "-"*

As mentioned in section II, the change-over form "+" to "-" gives different results for the recovery voltages and switch currents compared to the results while the change-over starts to move from "-" to "+". Considering this, the results of the recovery voltage, V_{R+}, and the switch current are investigated in this section. Fig. 6 a and b show the simulation results for V_{R+} and the switch current I_{switch}, respectively. As shown, for the first 0.4s, i.e., before change-over selector moves, the voltage of the stationary contact (+) is zero as Breaker1 is closed and the switch current is equal to 923 mA (pk). Exactly at 0.4s, the change-over selector starts moving towards the "-" contact, and Breaker1 is set to the "open" state, as the selector floats in between the contacts. There is a restrike which is due to the effects of the coupling capacitances and adjacent winding voltages from 0.4 s to approximately 0.47 s. The restrike extinguishes at around 0.47 s, and the switch current becomes zero. V_{R+} has a very high initial peak of 330 kV but soon settles to 188.312 kV (pk) for the remainder of the selector crossover time. For the Reinhausen M-type (delta-connected) OLTC as is the case here, the limit for the recovery voltage is 50 kV (pk) [13], and so this recovery voltage is not acceptable, indicating a necessity for a tie-in resistor which will be discussed in Section VI. At t=0.6s, the selector reaches the "-" contact signified by closing Breaker2, and V_{R+} now represents the voltage on the stationary contact (+) and is equal to the voltage of the tap winding, which is 15% of the HV winding giving a value of 48.79 kV (pk). The switch Current is now the current of the "-" contact, which is equal to 670 mA (pk), as Breaker2 is closed.

B. *Changeover from "- to "+"*

Now, to assess the results of the recovery voltage, V_{R-}, and switch current while the change-over selector moves from "-" contact to "+" contact, another simulation is performed. Fig. 7. a and b show the simulation results for the recovery voltage and the switch current when the change-over selector is initially connected to "-" contact. For the first 0.4s, the voltage of the stationary contact (-) is zero as Breaker2 is closed and the switch current is equal to 670 mA (pk), which signifies the current of the stationary contact (-). At 0.4 s, the change-over selector starts to move from "-" contact to "+" contact and Breaker2 is set as "open", and the selector floats between "-" and "+" contacts. From 0.4 s to around 0.47 s, restrike happens, and its amplitude is less than the restrike of the switch current when selector moves from "+" to "-". Then, approximately at 0.47 s, the restrike is extinguished, and the switch current is zero. V_{R-} reaches 140.16 kV (pk) for the remainder of the selector crossover time, which again is not acceptable. At t=0.6s, the selector reaches the "+" contact signified by closing Breaker1, and V_{R-} now indicates the voltage on the stationary contact (-) and is equal to the voltage of the tap winding. The switch current is now 923 mA (pk) and is the current of the "+" contact.

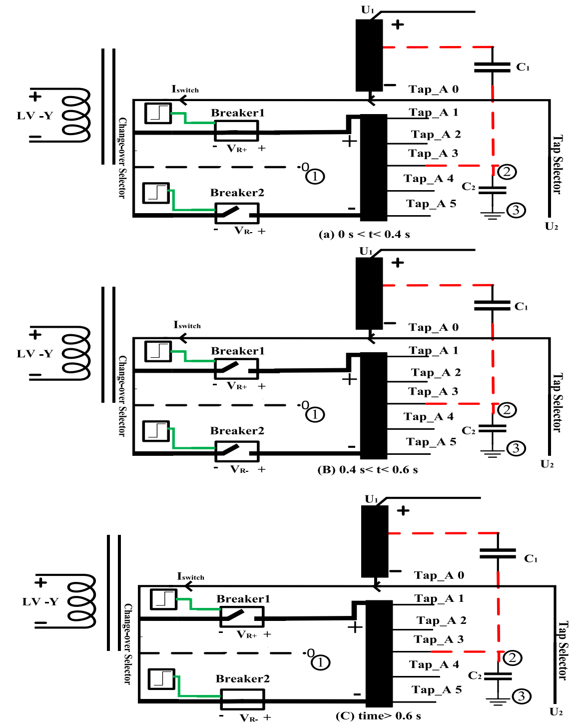


Fig. 5. Change-over selector position during the simulation (i.e. 0 s <t< 1 s).

Table II shows the comparison of the simulation and theoretically calculated results as calculated from equations (2), (3), (4), (5). The results are very close, with a maximum error of 2.3%, for both the recovery voltages and the switch current. The simulation model, however, shows much more transient detail in the restrike waveforms. Nevertheless, the close agreement between the simulation waveforms after fast transients have decayed, and theoretically calculated phasor values is an additional validation step for the simulation model.

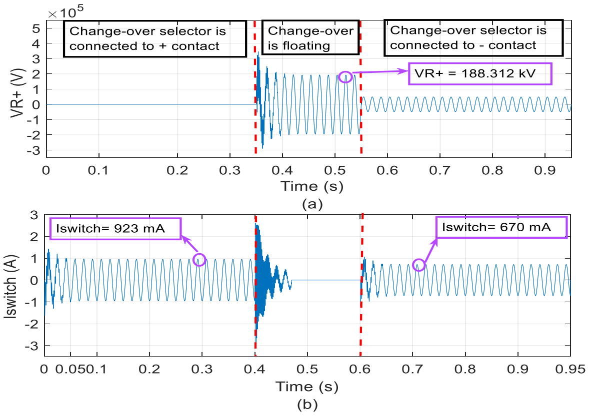
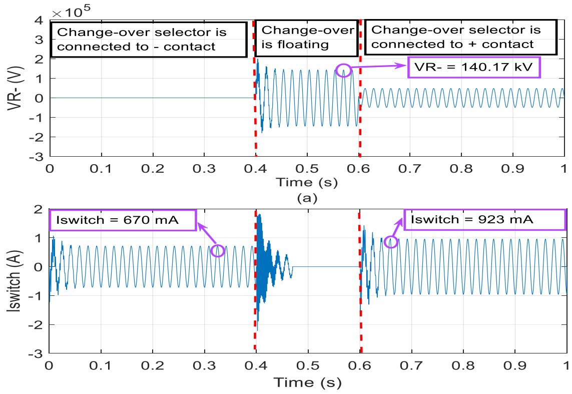


Fig. 6. The simulation result for (a) V_{R+} and (b) I_{switch} while the change-over selector moves from "+" contact to the "-" contact.



(a)

(b)

Fig. 7. The simulation result for (a) V_{R-} and (b) I_{switch} while the change-over selector moves from "-" contact to the "+" contact.

TABLE II

THE COMPARISON OF THE SIMULATION AND CALCULATION RESULTS

Changeover from "+" to "-"			Changeover from "-" to "+"		
V_{R+} (pk)			V_{R-} (pk)		
Calculated value	Simulated value	|Error| %	Calculated value	Simulated value	|Error| %
188.28 kV	188.312 kV	0.017%	139.92 kV	140.17 kV	0.172
I_{Switch} (pk)			I_{Switch} (pk)		
Calculated value	Simulated value	|Error| %	Calculated value	Simulated value	|Error| %
922.7 mA	923 mA	0.033	685.7 mA	670 mA	2.29%

VI. TIE-IN RESISTOR

The tie-in resistor R_{tie} is used if the recovery voltage and switch current exceed the permissible equipment limits. As shown in Fig. 8, The tie-in resistor is connected between the middle of tap winding and tap selector. It significantly improves the transient response while the change-over selector is floating as it reduces the recovery voltage and restrike current. Considering the results of the recovery voltages and switch current in section V, using the tie-in resistor is a necessity, as the permissible recovery voltage for the change-over switch is less than 50 kV [13]. The tie-in resistor reduces the recovery voltage and so greatly reduces the gas-in-oil production during arc quenching. They also significantly reduce the audible sound level which is due to the reduced arcing activity [14]. The resistance value is chosen in a way that the recovery voltage is limited to a permitted value which is stated in the technical guides for each tap-changer. In this simulation, the Reinhausen M-type (delta-connected) OLTC has been considered, the limit for the recovery voltage for this type is 50 kV (pk) [13]. Fig. 9. a and b show the equivalent circuit of Fig. 8 for the calculation of the switch current and recovery voltages. From Fig. 9. a and b, the value of the (post-transient) switch current and recovery voltage can be calculated by phasor analysis. the recovery voltage can be calculated by (8). The maximum allowable voltage is kept to 48 kV (i.e., smaller than the 50 kV from [13]), giving a tie-in resistor value of 50 kΩ as shown in (9). Also, the switch current for "+" and "-" contact can be calculated by (10) and (11), respectively.

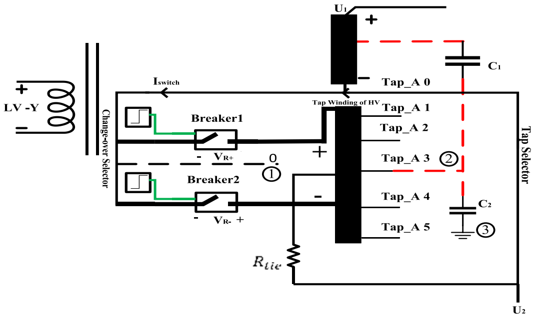
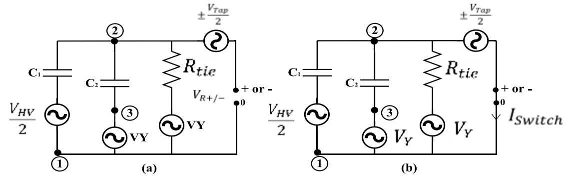


Fig. 8. The arrangement of the proposed model with the tie-in resistor.



(a)

(b)

Fig. 9. The equivalent circuit to calculate (a) the recovery voltage (b) the Switch currents with the tie-in resistor.

$$|V_{R\pm}| = \sqrt{2}\left|\frac{\frac{V_{HV}}{2}(R_{tie}||Z_{c2})}{(R_{tie}||Z_{c2}) + Z_{c1}} - \frac{\frac{V_Y}{2}(R_{tie}||Z_{c1})}{(R_{tie}||Z_{c1}) + Z_{c2}} \pm \frac{V_{Tap}}{2}\right| \tag{8}$$

$$Max(|V_{R\pm}|) = 48\ kV \overset{So}{\rightarrow} R_{tie} = 50\ k\Omega \tag{9}$$

$$|I_{Switch}| = \sqrt{2} \times \left|\frac{\frac{-V_{Tap}}{2} - \frac{V_{HV}}{2}}{Z_{c1}} + \frac{\frac{-V_{Tap}}{2} + \frac{V_Y}{2}}{Z_{c2}} + \frac{-\frac{V_{Tap}}{2}}{R_{tie}}\right| = 1092\ mA \tag{10}$$

$$|I_{Switch}| = \sqrt{2} \times \left|\frac{\frac{V_{Tap}}{2} - \frac{V_{HV}}{2}}{Z_{c1}} + \frac{\frac{V_{Tap}}{2} + \frac{V_Y}{2}}{Z_{c2}} + \frac{\frac{V_{Tap}}{2}}{R_{tie}}\right| = 777\ mA \tag{11}$$

The change-over is initiated at 0.4 s, and takes 200 ms for the selector to move across the contacts. Fig.10. a and b show the simulation results for the V_{R+} and switch current with the tie-in resistor while the change-over selector moves from the "+" to "-" contact. For t < 0.4 s, V_{R+} is zero and I_{switch} of the "+" contact is 1100 mA (pk), which closely agrees with the theoretical calculation of 1092 mA (pk). Note that this is larger than the current of 923 mA without the tie-in resistor. It is marginally larger as the resistor adds a real component to the leading capacitor current. The initial high frequency peak in the recovery voltage is now completely eliminated, and V_{R+} attains a value of 47.8 kV which is much smaller than the 188.312 kV value without the tie-in resistor in Fig. 6. a. After selector crossover (i.e., t > 0.6 s), the voltage of the stationary contact

(+) is equal to the voltage of the tap winding of 48.79 kV (pk). Also, the switch current into the "-" contact is 800 mA (pk), which is (calculated value of 777 mA). Similarly, the results for the switch current and V_{R-} is shown in Fig. 11. a and b while the change-over switch moves from "-" contact to "+" contact. Before switch-over (i.e. t< 0.4 s) the switch current (into the "-" contact) is 800 mA (pk). The transient part is improved significantly for the switch current and the recovery voltage. The recovery voltage value, V_{R-}, settles in 36 kV (pk) (i.e., below the 50 kV limit) which is also much smaller than the 140.2 kV (pk) without the tie-in resistor in Fig. 7. a. After changeover (i.e. t>0.6 s), the switch current is 1100 mA (pk). The voltage of the "-" contact will be equal to the tap winding voltage of 48.79 kV (pk).

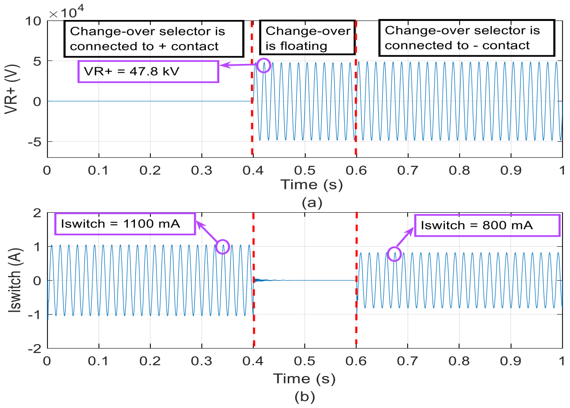


Fig. 10. The simulation results for (a) V_{R+} and (b) I_{switch} with the tie-in resistor while the change-over selector moves from "+" contact to the "-" contact.

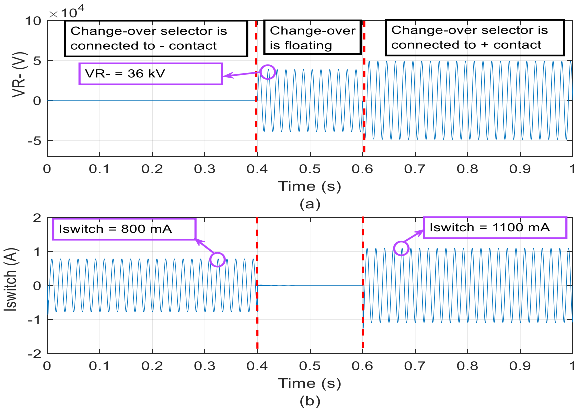


Fig. 11. The simulation results for (a) V_{R-} and (b) I_{switch} with the tie-in resistor while the change-over selector moves from "-" contact to the "+" contact.

VII. CONCLUSIONS

In this paper, the transient behavior of the OLTC during change-over process is investigated. Firstly, a steady-state model for OLTC during change-over operation is presented. This model provides a good approximation for the recovery voltages and switch current. Secondly, the Mayer's arc model in MATLAB is reviewed. Then, this paper introduces additional breakers with Mayer's arc model, and these breakers are connected to the "+" and "-" selector contacts to represent the selector transitioning between "+" and "-" contacts. Apart from that, the proposed model considers the effect of winding capacitances which are the important parameter in the determination of the transient as well as the steady state change-over selector switch current and recovery voltages. Due to the unavailability of experimental results, confidence in the simulation results of the transient model was improved by the close comparison with steady-state theoretical calculations. Considering this, the proposed model is simulated in MATLAB software. the simulation results are matched with theoretical results with the error of less than 2.5%. The model was also effective in determining the effect of using a tie-in resistor on recovery voltage and selector switch current. Simulation results showed that the tie-in resistor enhances the transient behavior of the switch current and the recovery voltages while the change-over selector is floating.

VIII. ACKNOWLEDGMENT

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