# RC filter to protect industrial arc furnace transformers during switching–off

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*Abstract*: – It is really important to correctly design the devices that will protect the transformer from over–voltages and voltage oscillations that can occur at the arc furnace transformer terminals. These devices, the RC filters and the surge arresters, are employed to smooth dangerous over–voltages that could severely damage the transformer insulation system.
The over–voltages usually happen during switching on and switching off operations, that in this kind of application occur very frequently (up to one hundred times per day).
Another important task of transformer protection devices is to prevent current re–striking when interrupting the circuit and the consequent voltage escalation phenomenon. The purpose of the following study is to discuss the problem of switching off transients concerning industrial electric arc furnace transformers, particularly regarding the eventuality of breaker re–striking during the switching operation.
This study demonstrates the necessity of simulating the plant circuit transient in order to determine the right protection devices as RC filters for furnace transformers.

*Key–Words*: – arc furnace, furnace transformer, switching off transient, breaker re–striking, chopping level current, vacuum circuit breaker, over–voltage

## 1 Introduction

A typical plant circuit can be represented as follows in Fig. 1. It is important to evaluate carefully each parameter of the equivalent model of the plant under study, because the calculation of the protection devices is strongly affected by the plant parameters. A variation of one of these parameters would require a new check of the devices calculation, so it is essential to study the circuit with caution.

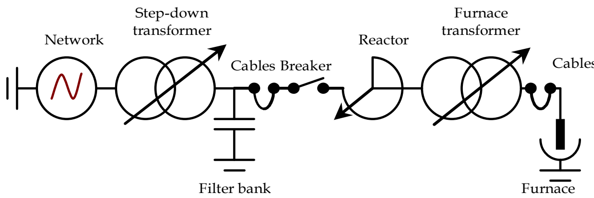


*Fig. 1 – Plant model*

As known, transformers for electric steel production have to endure severe duty cycles suffering several times a day switching on and off operations [1] [2]. Due to the high number of operations these plants employ vacuum circuit breakers (VCBs) that are devices able to join an excellent breaking capability with long life of the equipment. The energy developed is significantly higher for other kinds of breaker. The usage of vacuum as interruption mean is also great for the breaker durability, because it is able to ensure the lack of agents that could damage the contacts or the insulating materials (a problem specially affecting SF6 breakers). This is a positive feature because it keeps the contacts clean, thus maintaining the contacts resistance constant for the whole breaker life. Durability is also affected by the material employed for the poles chamber. In fact, if this was synthetic, for example epoxy resin, the high temperatures would damage the chamber. Vacuum circuit breakers adopt ceramic materials, unaffected by temperature. It is important to adopt mechanical solutions that guarantee the vacuum into the interruption chamber. Another positive feature of the vacuum circuit breaker is that, due to the already mentioned low usage of synthetic insulating materials (that could burn), this kind of breaker reduces the risk of fire hazard. The vacuum breakers are also more reliable, for the reasons reported above, and because they have less moving parts than other breakers have, too, see Fig. 2. Furthermore, oil (gas) breakers interruption ability is influenced by oil (gas) relative motions, while in the vacuum circuit breaker this cannot happen because its performances are depending on the contacts separation only [3]. Anyway, SF6 breakers have generally better electrical performances, indeed they are practically free from risk of re–strike events. Their main disadvantage is, as already stated, related to the relatively reduced endurance (25000 operation vs. 250000 for the VCBs).

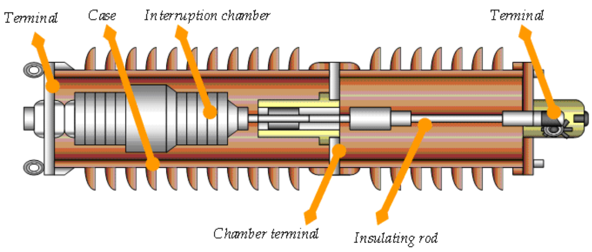


*Fig. 2 – Vacuum circuit breaker*

Unfortunately these breakers could generate hazardous over–voltages that could cause severe transformer electrical faults. This is due to the breaker strong interruption capability that allows the breaker interrupt currents up to 10A. Thus, the current could be chopped before its natural zero value, generating harmful over–voltages [4] [5] [6]. Furthermore, if immediately after the opening the over–voltage exceeds the dielectric strength of the breaker (this occurs when the breaker opens just before the current crosses the breaker chopping level, so that shortly after the breaking the breaker contacts are still too close to each other to endure the over–voltage) a current re–strike occurs. If the re–strike current re–approaches quickly the breaker chopping level, the current is interrupted once more, generating an over–voltage higher than the previous one. In the worst occurrence, this could happen several times, leading to a severely dangerous over–voltage escalation. The protection devices used against this kind of events are RC filters (snubbers) [7].

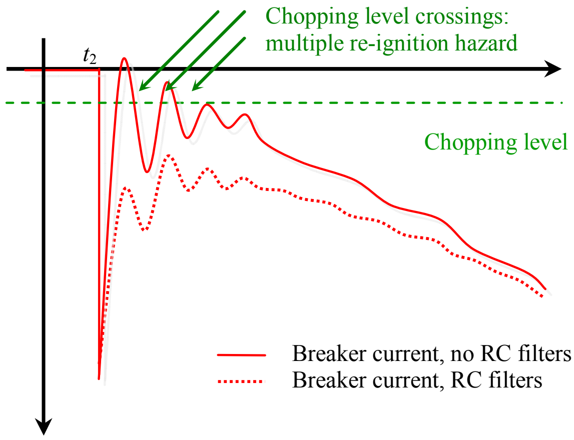


*Fig. 3 – Current detail after re–strike*

The purpose in employing RC filters, as shown in Fig. 3, besides damping the switching over–voltages, is damping the re–strike current in order to keep it away from the breaker chopping level thus making the breaker interrupt the current at its next zero value crossing and avoid multiple re–strikes. The re–strike phenomenon and the RC filter protection system has been studied by single–phase and three–phase simulations performed employing the simulation program ATP (Alternative Transient Program).

## 2 Simulating with the ATP program

Using ATP, is possible to simulate the whole steel plant. In particular, it is possible to simulate the transformer even with its saturation characteristic, letting a more accurate simulation be performed. This model is anyway a simplified model, and does not simulate multiple re–strikes. Its purpose is to verify that the re–ignition current is kept away from the chopping level leaving a reliable gap able to make the multiple re–strike hazard be avoided. The re–strike phenomenon is simulated using two switches time controlled in parallel (VCB and ReVCB) as shown in Fig. 4.

The element called VCB is the main breaker, while ReVCB is the component that takes care of the re–striking behaviour. In series with these two breakers, resistances have been placed to take into account the resistance of the breaker when closed ($R_1$), and the resistance of the arc during re–strike ($R_2$). A small capacitance ($C_1$) has been placed in parallel in order to simulate the breaker capacitance while the breaker is opened. The model accuracy is fundamental in order to obtain reliable results. Three phase and single phase simulations have been performed. Single phase simulations are quite good already, but three phase simulations are surely more accurate, and let study the interaction among the three phases during the breaker operations [8], in particular the virtual current chopping effect [9].

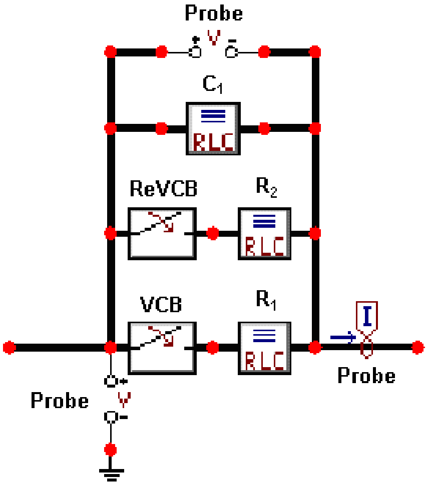


*Fig. 4 – simplified breaker model*

In a three–phase system it is really improbable that the three poles of the breaker open at the same time. In this condition if the first opening pole is subject to a multiple re–ignition, its high frequency re–ignition current would re–close through the other poles passing into the cable capacitances. The sum of the normal load current and the returning high frequency current could lead to a sudden fall of the instantaneous value of the total resulting current close to zero (as shown in the following Fig. 5). Thus, the vacuum circuit breaker pole could interrupt the load current before its natural passage across the zero value and this would lead to over–voltages similar to the current chopping phenomenon described above, with a significant over–voltage. The effect could be a possible double magnitude transient on phase–to–phase voltage. The virtual chopping effect is remarkable when the system has the neutral isolated and there is a considerable inductive coupling among the three phases, as for example when relatively long bus bars are employed to connect the breaker to the transformer.

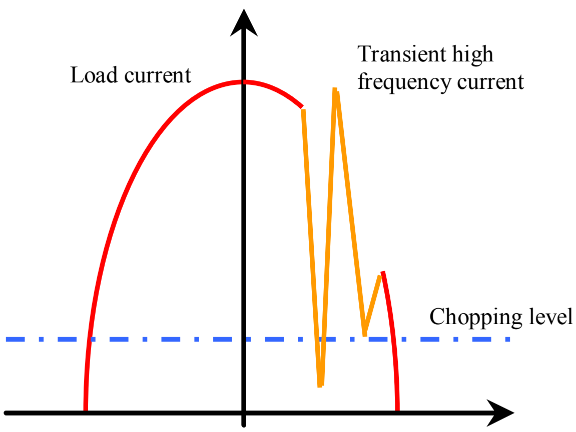


*Fig. 5 – Virtual current chopping*

In this situation the re–ignition current can completely re–close through the other poles. Of course, three phase simulations are also more complex. Another issue to consider is the representation of the load. A simple equivalent AC load model is acceptable, but more precise results would be obtained considering the variability of the arc resistance in various working points of the furnace. A more complex modelling of the load can enhance the results accuracy, but increases largely the amount of cases to study and this makes the number of simulations to perform grow significantly. Therefore, the simulation tool have to be flexible enough to allow many levels of precision in order to satisfy various user's requirements.

## 3 No load behaviour

Concerning the no load switching off [10], the main purpose of the RC filter is smoothing the over–voltage. Using RC filters has a strong impact on the transformer over–voltages, confirming it as a reliable protection device. This kind of trial has been simulated opening the VCB when the no load breaker current was at its maximum (in order to ensure the highest current chopped), while the ReVCB breaker was left open, being not involved in this kind of simulations.

## 4 On load behaviour

As already stated, the on load switching off is affected by the re–ignition problem.

Fig. 6 shows the typical circuit considered for multiple re–strike phenomenon.

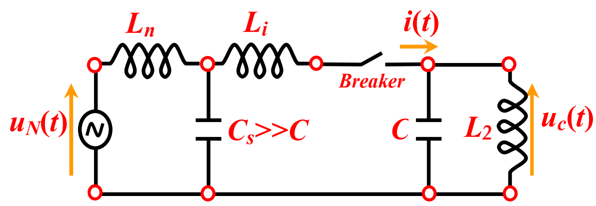


*Fig. 6 – Typical circuit*

Where $u_N(t)$ is the phase voltage source; $L_n$ the sum of power system and the step down transformer short circuit inductance; $L_i$ the cable inductance; $C_s$ the power factor capacitance; $C$ the transformer stray capacitance; $L_2$ the sum of load and transformer short circuit inductance; $i(t)$ the breaker current; $u_c(t)$ the phase to ground voltage at transformer terminals.

Without RC filters, multiple re–ignition could occur, as shown in Fig. 7 and in the following described.

Assuming that the breaker opens at natural current zero value, the power factor capacitance $C_s$

stays charged to the voltage $u_0$ (phase voltage at the time of breaker opening). The voltage across the capacitance $C_s$ can be considered constant because of the capacitance bigness (in the time interval kept in consideration).

At the time $t_0$, the transformer capacitance $C$ starts to discharge into the inductance $L_2$, and then recharges almost to the same voltage value with opposite polarity (not considering losses).

At the time $t_1$, the gap between $u_0$ and $u_c$, that is the voltage across the breaker, could overtake the dielectric strength of the breaker contacts. This makes a breaker re–ignition occur. The capacitance $C_s$ (power factor capacitance) charges the capacitance $C$ trough the inductance $L_2$ and the voltage swings symmetrically around $u_0$.

At the time $t_2$ the re–ignition current $i_R$ crosses again its natural zero value. At this time, the breaker is able to interrupt the current once more. The stray capacitance $C$ discharges again through $L_2$, making it possible to a new re–ignition occur, in the eventuality that the dielectric strength of the circuit breaker is still not high enough.

Having the breaker contacts further separated, the voltage reached during the second re–ignition is higher than the first one. If this re–ignition just described occurs several times, it leads to a voltage escalation, a sequence of increasing peaks of voltage [11], as shown in Fig. 7.

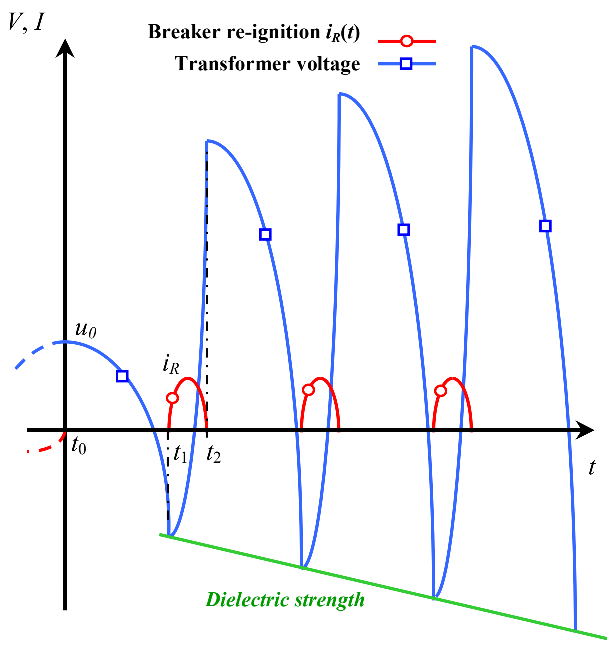


*Fig. 7 – Multiple re–strikes*

This phenomenon is stopped when the distance between the contacts is long enough to provide an adequate dielectric strength, able to withstand the voltage across the breaker. Furthermore, instead of leading to these multiple re–ignitions, the breaker could fail to interrupt again the circuit after the first re–ignition and conduct until the current reaches its next natural zero value, when the breaker can successfully interrupt the circuit (the goal in designing the RC filters). During the re–charging of the capacitance $C$, the oscillations are usually slightly damped, due to the circuit resistances.

However, the high frequencies of this phenomenon deals with can be hazardous for the transformer, because they could even be similar to the natural resonance frequencies of the transformer windings, thus causing a significant dielectric stress to the transformer windings.

The purpose of RC filters is thus to prevent the re–strike current from re–crossing the chopping level immediately and being chopped. If the filter is correctly designed, after the first re–strike the current is not chopped again until its next natural zero value passage.

## 5 Simulating the plant

In the following table 1 and table 2 are reported the essential data of the plant and the transformer used to simulate the furnace power plant. Please note that network short circuit power can assume different values, only the most hazardous has been reported.

| **Network data** | |
|---|---|
| Network rated voltage | 33kV |
| Network short circuit power at 33 kV | 300 MVA |
| Frequency | 50 Hz |
| Filter bank power | 100 MVAr |
| Cable length (to reactor) | 25 m |
| Cable length (from reactor) | 775 m |
| Cables per phase | 3 |
| Cables inductance | 0.11551 mH |
| Bus bars length | 25 m |
| Reactor losses | 92 kW |

*Table 1 – Network data*

| **Transformer data** | |
|---|---|
| Power | 78 MVA |
| Primary rated voltage | 33 kV |
| Secondary voltage | 1.1 kV |
| No load losses | 61 kW |
| No load current % | 0.17% |
| Short Circuit losses | 335 kW |
| Short Circuit voltage % | 8.06% |

*Table 2 – Transformer data*

Finally, the filter has been calculated according to the procedure indicated in the reference [12].

$$C = 90 \cdot \frac{i_{0\%} \cdot A}{f * V_n^2} = 90 \cdot \frac{0.17 \cdot 78}{50 \cdot 33^2} = 0.022\mu F \rightarrow 0.2\mu F$$

On the basis of experienced cases, the calculated capacitance is increased to 0.2$\mu F$. This value of capacitance should guarantee a good performance in terms of over–voltage limitation joined with a reasonable power rating of the resistor.

$$R > 2 \cdot \sqrt{\frac{L_c}{C}} = 2 \cdot \sqrt{\frac{0.11551 \cdot 10^{-3}}{0.2 \cdot 10^{-6}}} = 48.064\Omega \rightarrow 70\Omega$$

In the above formulas $i_{0\%}$ is the transformer no load current, $A$ the transformer rated power [MVA], $L_c$ the connection cables inductance [H], $V_n$ the HV rated voltage [kV] and $f$ is the network frequency [Hz]. It has also been considered the existence of a stray inductance of the filter resistance of 50 μH, a value known by the resistance construction features. In Fig. 8 the furnace power plant obtained using the data listed above is shown.

## 6 No filters trials

Before designing and testing the protections, the switching off transient will be checked without the RC filters. This will let appreciate better the RC filters efficiency in smoothing an over–voltage that could be far more heavier. The trials have been performed in different network and plant conditions. Worst results will be reported. Results have been shown in the figures 9 and 10.
First of all, the no load trial. As displayed in Fig. 9, after opening ($t_1$) the over–voltage peak (transformer voltage line, $t_2$) is quite sharp, resulting in a significant over–voltage (approximately 108kV in a 33kV network).

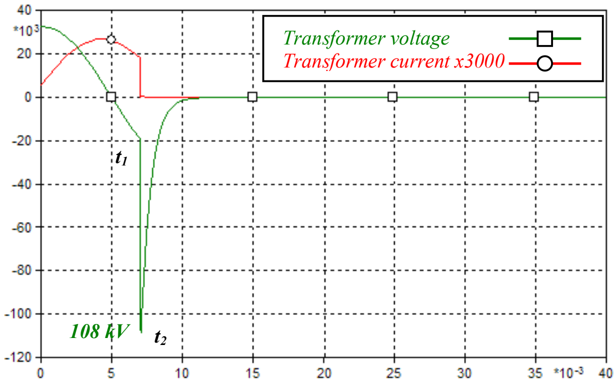


*Fig. 9 – No load switching off, no RC filters*

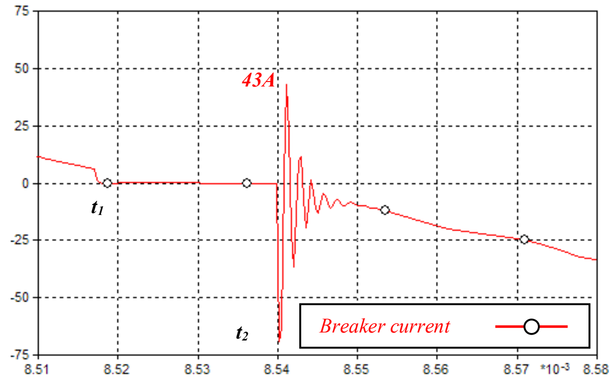


*Fig. 10 – On load switching off, no RC filters*

Then, the on load trial, during which the re–strike current, as shown in Fig. 10, crosses the current zero value multiple times, exposing the breaker to the risk of a multiple re–strike.

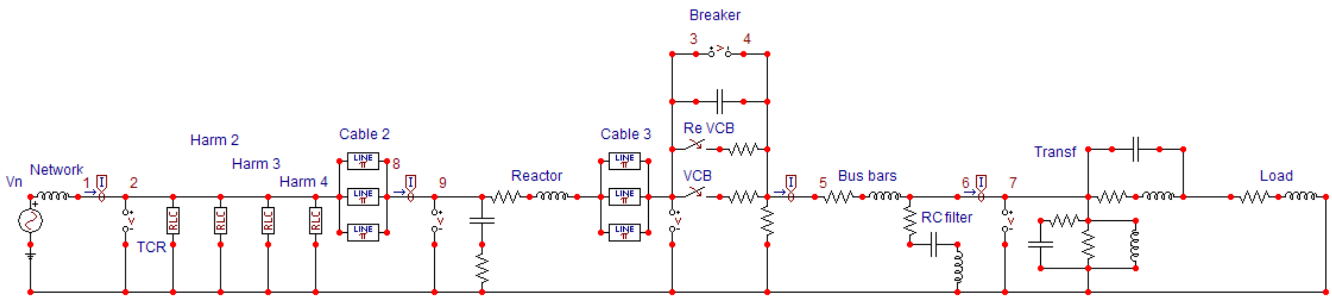


*Fig. 8 – Furnace power plant*

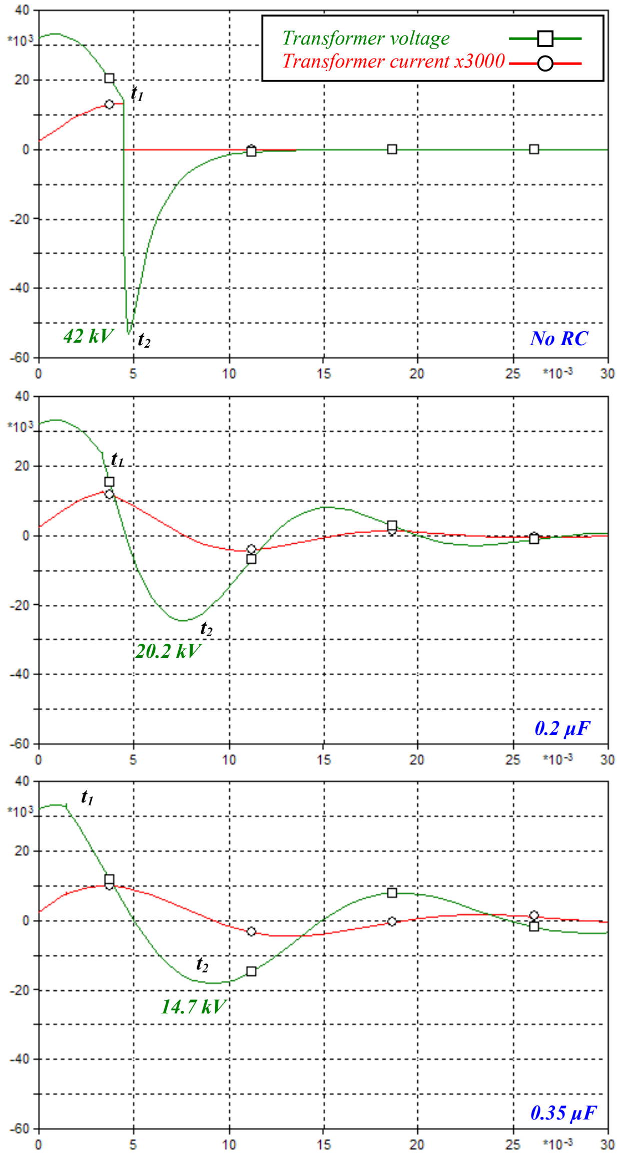


*Fig. 11 – No load switching off in different conditions*

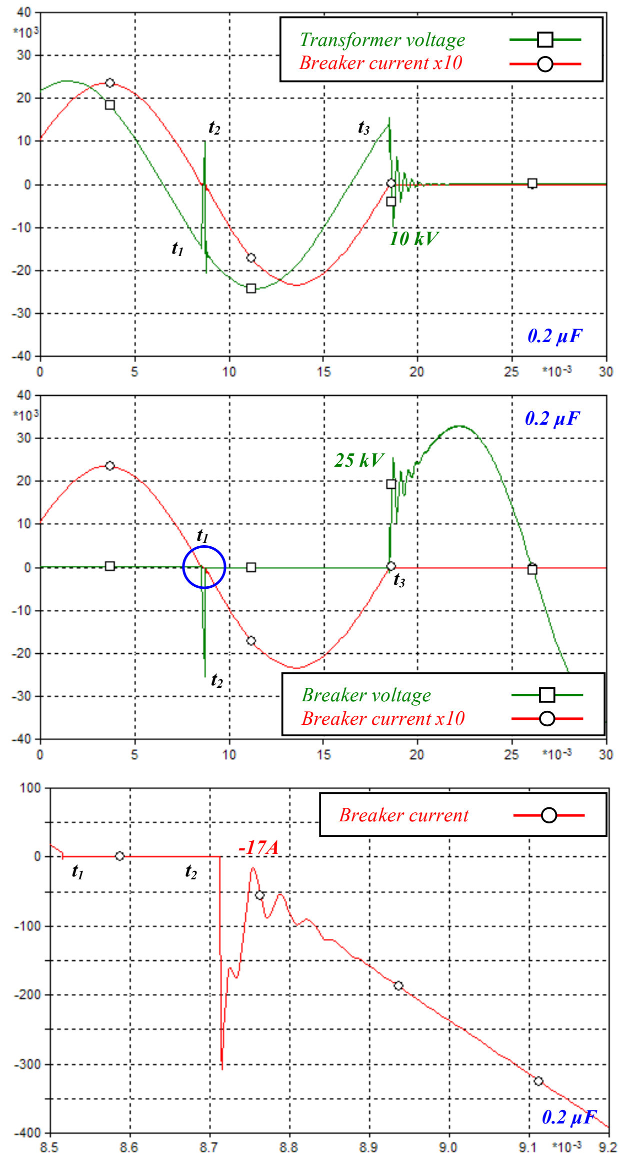


*Fig. 12 – 0.2µF filter on load trial*

After the first opening of VCB ($t_1$), ReVCB is closed at time ($t_2$) when the breaker voltage reached a typical re–striking value. Without RC filters, the re–strike current crosses its zero value (in this example reaching 43A). This zero value crossing is the typical hazardous situation that leads to a multiple re–strike and can usually occur when RC filters are not employed or have not a suitable value of capacitance.

## 7 RC filters trials

The same trials have been performed again using, this time, the RC filters testing two different values of capacitance: 0.2$\mu F$ and 0.35$\mu F$.

The filter resistance have been set to 70Ω. First, the no load trials.

In Fig. 11 are shown the results for "no filters", "0.2$\mu F$" and "0.35$\mu F$" trials. Time $t_1$ is when the breaker opens, while time $t_2$ is when the over–voltage peak is reached.

As displayed in Fig. 11, the over–voltage peak is significantly reduced using a filter with a 0.2$\mu$F capacitance, and is slightly smoothed even further increasing the capacitance to 0.35$\mu$F. Increasing the capacitance raises even the peak reaching time, in these trials up to 4ms.

Finally, RC filter on load behavior will be checked. Even these trials have been performed testing the two different values of filter capacitance 0.2$\mu$F and 0.35$\mu$F.

At the time $t_1$ the first interruption occur, while $t_2$ is re–strike time. At $t_3$ the current is successfully interrupted. This has been simulated first opening VCB ($t_1$), then closing ReVCB ($t_2$) when the breaker voltage reached a typical re–striking value. ReVCB re–opens at $t_3$, when the current is interrupted.

The re–strike current is held away from the chopping level, avoiding the occurrence of a multiple re–strike.

A better value could anyway be obtained using an higher value of capacitance. The results of the $0.35\mu$F trial are shown in Fig. 13.

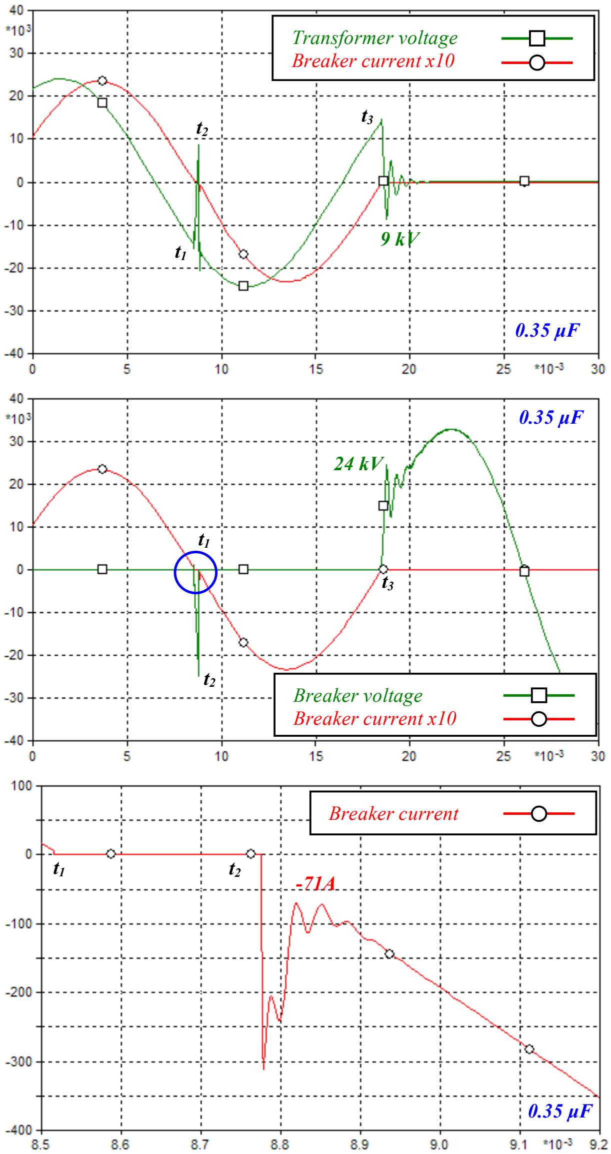


*Fig. 13 – 0.35μF filter on load trial*

The re–strike current is once again held away from the chopping level, preventing multiple re–strike, but with a much safer gap between the current lowest value and the current chopping level. Anyway, it is not possible to raise the capacitance value at will, because it must be pointed out that a higher capacitance means a lower impedance, and consequently more current normally flowing into the RC filter and finally higher power losses in the filter resistance. The correct value must be a compromise between protection needs and power consumption.

## 8 Conclusions

The usage of protection devices in employing arc furnace transformers is fundamental to limit the enormous stresses these machines must suffer during their common life. Furnace transformers have to endure very heavy solicitations, many times per day. In order to ensure service continuity, and prevent serious damages, protections design and employment is absolutely necessary.

It is also possible to state that ATP, able to permit the study of many kinds of issues allowing various levels of precision depending on the user's demands and resources, is a really powerful simulation instrument. In particular, when simulating industrial transformer protection devices the program makes the user able to study with great precision the transient behaviour and the impact of the protection system on it.

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