IMPACT OF TRANSFORMER-LIMITED FAULT ON TRV OF MEDIUM VOLTAGE CIRCUIT BREAKERS IN INDUSTRIAL PLANTS

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Abstract - In medium voltage distribution of industrial plants there is sometimes the need to limit the short circuit fault currents, due the increasing power of distribution transformers for applications at 4.16 kV to 10 kV, or in the scenario of using a meshed grid by making two transformers to work in parallel at these voltage levels.

The practice of increasing the short circuit impedance of transformers can be an affordable solution to limit the fault current below the withstand capability of medium voltage switchgear equipment, avoiding for example the use of additionally air-core reactors to be installed in series to the distribution transformer incomer feeders.

However, the stray capacitances of the transformer windings and bushings causes a very high steepness in the rate of rise of TRV (Transient Recovery Voltage) just few moments after fault current interruption, and circuit breaker failure can result.

Electromagnetic transient studies are performed in order to specify the most suitable TRV test duty in accordance to the applicable IEC standards for circuit breakers.

Index Terms — Transformer-limited fault, TRV, rate of rise of recovery voltage, short circuit impedance, stray capacitance.

I. INTRODUCTION

When performing short circuit current calculations according to well-known reference international standards [1], [2], it is a common widespread practice to check only the maximum fault current duty of switchgear equipment and not also the TRV (Transient Recovery Voltage) developed across circuit breaker poles. This approach seems reasonable and justifiable for most industry applications where usually there are no special cases whereby the TRV can become a concern [3], [4], like for example medium voltage generator circuit breakers in power stations, or extra-high voltage (≥ 100 kV) circuit breakers which feed overhead lines, shunt reactors, or series reactors for fault current limiting.

For those medium voltage applications where the scenarios of transformer-limited faults (also named transformer-fed faults [5], [13]) are predominant in determining the magnitude of short circuit currents, the aim of this work is to highlight the importance of checking also the TRV requirement of medium voltage circuit breakers as well as the importance of specifying the correct short circuit test duty to the switchgear manufacturer.

A. System Data

The principle of the electrical distribution scheme of an industrial refinery facility, in which the plant loads are fed by two 110 / 10.5 kV / 10.5 kV transformers, is shown in Fig. 1. The two transformers are operating in parallel on the 10 kV busbars.

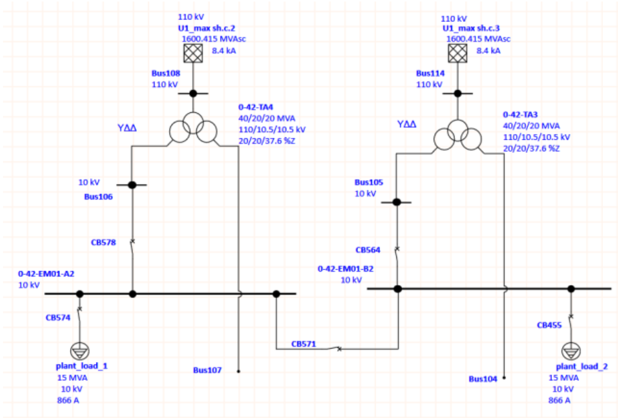

Fig. 1 Simplified single-line diagram of the electrical system

Main electrical parameters for the network components are reported in the Appendix.

B. Modeling

For the aim of numerical simulation of electromagnetic transient recovery voltage by EMT analysis software [7], the electrical network is simplified and modeled as shown in Fig. 2, following the general guidelines presented in [8].

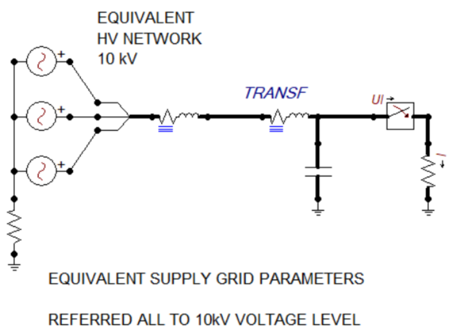

Fig. 2 EMT analysis software model of the electrical system

All equivalent impedances of the network components are referred to the switchgear busbar voltage level of 10 kV for which the TRV of circuit breaker is studied.

Main transformer is modeled by means of its short circuit impedance.

The equivalent impedance of the 110 kV supply network is derived from the corresponding value of available maximum short power at the point of common coupling of the industrial plant to the supply grid.

The stray capacitance to earth value of transformer bushing is provided by relevant manufacturer information.

The 3-phase short circuit fault is simulated by applying an almost null resistor (0.001 ohm) across the terminals of the breaker.

The vacuum circuit breaker of the 10 kV switchgear incomer feeder is modeled as time controlled ideal switch, that is a switch that opens at a pre-determined time, and considering simultaneous breaking among poles. The arc quenching behavior of the vacuum circuit breaker is not modeled, because the intention of this work is not to study the phenomena of reignitions, restrikes and non-sustained disruptive discharges which could occur inside the vacuum interruption chamber during the breaking, and since the vacuum circuit breaker is of type C2 (that is with very low probability of restrikes) as per relevant IEC standards [5]. Therefore, the aim of this study is to evaluate the inherent TRV at breaker terminals [4], [10], occurring during a 3-phase short circuit fault opening operation of the breaker.

C. *Case Study*

The scenario of a transformer-limited fault is studied as shown in Fig.3: a short circuit fault occurs inside the switchgear busbars zone and the switchgear incomer circuit breaker has to clear the short circuit fault contribution limited by the impedance of the supply transformer.

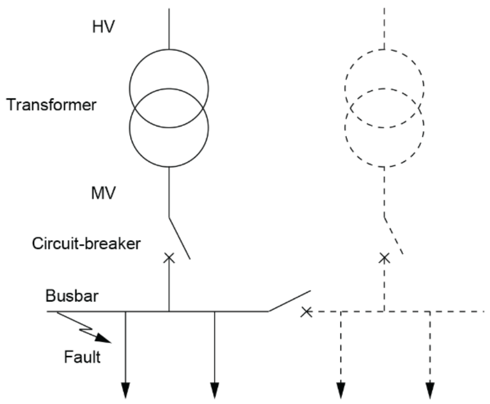

Fig. 3 Transformer-limited fault (Transformer-fed fault)

Since the breaking current for the transformer incomer breaker is only a fraction of the total short circuit current of the busbars, and this fraction typically ranges from 10% to 30% of the rated short circuit withstand of the switchgear, the test-duty T30 is normally specified to prove the capability of a circuit breaker to interrupt transformer-limited faults [5].

For the specific application studied here, the 10 kV switchgear equipment insulation is designed according to IEC standard [6], which means a minimum rated insulation voltage of 12 kV for the switchgear being operated at 10 kV voltage level. Therefore, the initial selection of test-duty TRV envelopes for the circuit breakers of the switchgear will be refereed to 12 kV rated insulation voltage.

II. SHORT-CIRCUIT CURRENT ANALYSIS

Here after the short circuit withstand rating of the 10 kV switchgear is first determined on the basis of power frequency short circuit study by means of RMS simulation software [9].

A. *Maximum short circuit rating of 10 kV switchgear*

A short circuit simulation is performed to first check the maximum 3-phase fault level, as shown in Fig. 4.

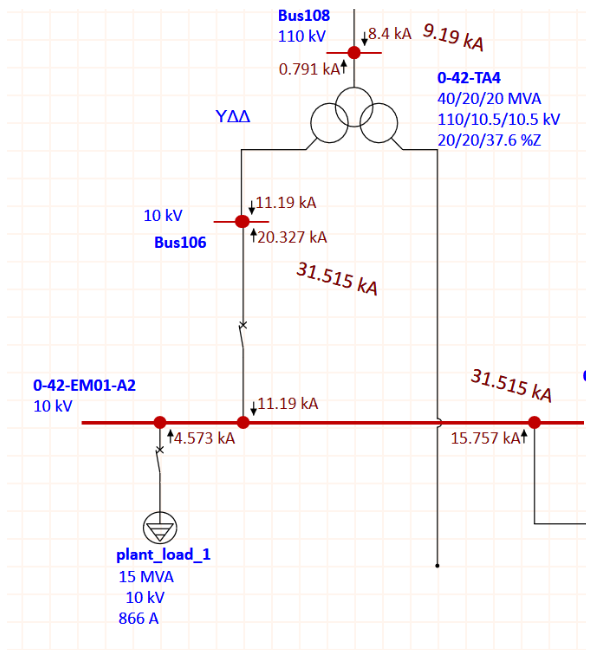

Fig. 4 Short circuit calculation (50 Hz, RMS values)

The maximum calculated short circuit current is equal to 31.5 kA (initial symmetrical RMS value) for a 10 kV busbar fault. It is therefore necessary to select a switchgear having a short circuit withstand rating of 40 kA (test-duty T100), initial symmetrical RMS value.

However, each transformer incomer circuit breaker interrupts only a fault current of 11.19 kA in case of busbar fault, that is only 28% magnitude with respect to the 100% short circuit test-duty (T100).

It is more appropriate to verify the short circuit withstand of the incomer breaker with test-duty T30 which covers 30% (12 kA) of the maximum switchgear rating.

III. ELECTROMAGNETIC TRANSIENT ANALYSIS

The TRV occurring across the poles of the transformer incomer circuit breaker is determined through EMT analysis software [7], and it is compared with the withstand TRV envelope given by the IEC standard [5] used for the design of the switchgear circuit breakers.

A. TRV for IEC test-duty T30 (12kV normal design)

According to reference IEC standard for high voltage circuit breakers [5], for 12 kV rated insulation voltage, the prospective TRV envelope for the test-duty T30 is defined by two parameters:

- maximum amplitude: 25.6 kV peak
- rise time: 10.6 µs.

These TRV parameters apply for the usual standard design of breakers typically applied by most manufacturers for medium voltage switchgears.

The phase A is taken as most representative for the worst condition of calculated TRV, as shown in Fig. 5: the simulated TRV is compared with the prospective standard TRV envelope.

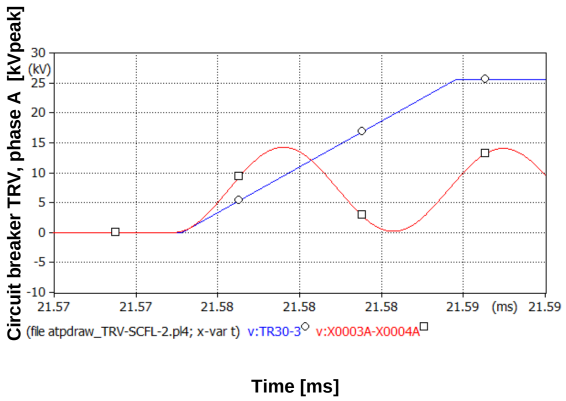

Fig. 5 Simulated TRV versus T30 test-duty TRV (IEC 62271-100, Table 18, 12 kV insulation)

As can be seen, the actual TRV exceeds the prospective envelope and therefore the circuit breaker can be damaged while interrupting the short circuit fault. The high steepness in the rate of rise of TRV is due to the small stray capacitance to earth of transformer winding.

A possible countermeasure is to require an enhanced design of the circuit breakers, in accordance with what foreseen by IEC standard for applications where transformer-limited faults are experienced [5].

B. TRV for IEC test-duty T30 (12kV enhanced design)

According to reference IEC standard for high voltage circuit breakers [5], for 12 kV rated insulation voltage, the prospective TRV envelope for the enhanced test-duty T30 is defined by two parameters:

- the maximum amplitude: 23.5 kV
- rise time: 6.73 µs.

These TRV parameters of test-duty T30 apply for the particular design of breakers which are intended to be connected to a transformer with a small capacitance.

The phase A is taken as most representative for the worst condition of calculated TRV, as shown in Fig. 6. The simulated TRV is compared with the enhanced prospective standard TRV envelope.

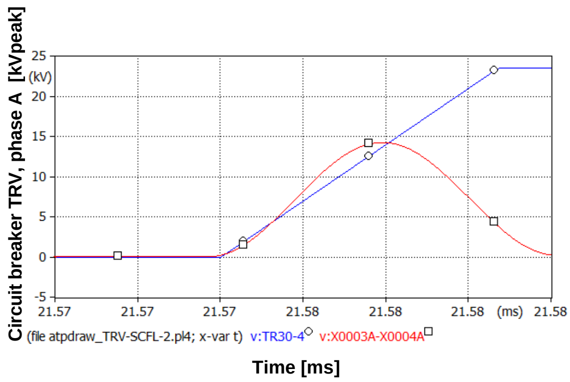

Fig. 6 Simulated TRV versus T30 test-duty TRV (IEC 62271-100-Annex F, Table F.1, 12 kV insulation)

As can be seen, the actual TRV again exceeds the prospective envelope of the enhanced test-duty T30 available in IEC standard 62271-100.

It is apparent that the TRV referred to 12 kV insulation voltage is not sufficient to satisfy the successful circuit breaker fault interruption, neither with normal nor with enhanced TRV design: it results necessary to increase the insulation rating of the circuit breakers to the next available level which is 17.5 kV as per IEC standard [6].

Both the normal and the enhanced design for TRV prospective envelopes will be checked again and compared with the simulated TRVs.

C. TRV for IEC test-duty T30 (17.5kV normal design)

According to reference IEC standard for high voltage circuit breakers [5], for 17.5 kV rated insulation voltage, the prospective TRV envelope for the test-duty T30 is defined by two parameters:

- maximum amplitude: 37.3 kV peak
- rise time: 13.8 µs.

These TRV parameters apply for the usual standard design of breakers typically applied by most manufacturers for medium voltage switchgears.

The phase A is taken as most representative for the worst condition of calculated TRV, as shown in Fig. 7: the simulated TRV is compared with the prospective standard TRV envelope.

As can be seen, the actual TRV exceeds again the prospective envelope and therefore the circuit breaker can be damaged while interrupting the short circuit fault.

A possible countermeasure is to require an enhanced design of the circuit breakers, in accordance with what foreseen by IEC standard for applications where transformer-limited faults are experienced [5].

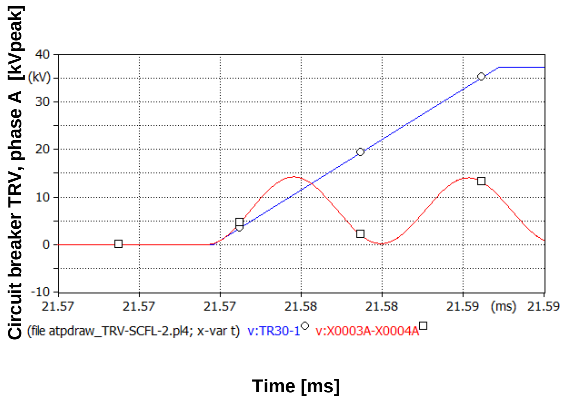

Fig. 7 Simulated TRV versus T30 test-duty TRV (IEC 62271-100, Table 18, 17.5 kV insulation)

D. TRV for IEC test-duty T30 (17.5kV enhanced design)

According to reference IEC standard for high voltage circuit breakers [5], for 17.5 kV rated insulation voltage, the prospective TRV envelope for the enhanced test-duty T30 is defined by two parameters:

- the maximum amplitude: 34.5 kV
- rise time: 8.05 µs.

These TRV parameters of test-duty T30 apply for the particular design of breakers which are intended to be connected to a transformer with a small capacitance.

The phase A is taken as most representative for the worst condition of calculated TRV, as shown in Fig. 8. The simulated TRV is compared with the enhanced prospective standard TRV envelope.

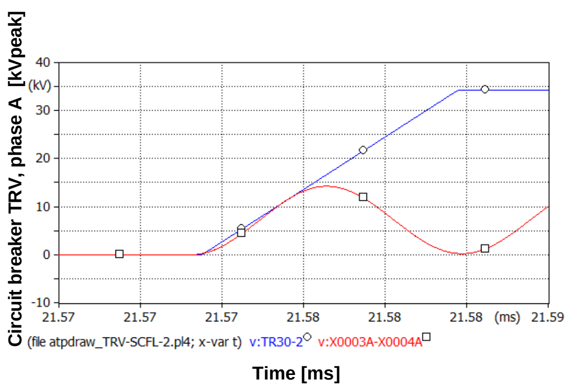

Fig. 8 Simulated TRV versus T30 test-duty TRV (IEC 62271-100-Annex F, Table F.1, 17.5 kV insulation)

As can be seen, now the actual TRV is within the prospective envelope of the enhanced test-duty T30 available in IEC standard 62271-100.

The enhanced TRV design of the circuit breakers will avoid special countermeasures described in technical literature [11], [12], [13], like installing additional capacitors between breaker terminals and earth in order to reduce enough the steepness of TRV.

IV. CONCLUSIONS

In industry applications there could exist some fault scenarios, like the transformer-limited fault (transformer-fed fault), for which the TRV duty requires due attention since an early engineering design stage: for some medium voltage distribution switchgears, when there is the need of reducing voltage interruptions and voltage dips in the supply to motor users, the transformers are operated in parallel on the same switchgear busbars, and therefore there is the need of increasing the short circuit impedance of transformers to satisfy the short circuit withstand rating of the medium voltage switchgear.

The scenario of a transformer having a very high impedance value is quite similar to the condition of having a faut current limiting series reactor: the stray capacitance to earth of the transformer winding can cause a very high steepness in the TRV while the circuit breaker interrupts the short circuit current having a small fault magnitude because it is limited by the transformer impedance.

Since circuit breaker for medium voltage switchgear are not intended to be equipped with additional capacitors between their terminals and earth, like it could easily happen instead for high-voltage / extra-high voltage breakers, the most affordable way to solve the issue for TRV of medium voltage breakers in case of transformer-limited fault conditions, is:

- to check the need of increasing the rated insulation voltage level of circuit breakers by one further grade: for example, for switchgear having 10 kV rated operating voltage and 12 kV rated insulation voltage, it can be necessary to use breakers with 17.5 kV rated insulation voltage, in place of breakers with 12 kV rated insulation voltage.
- To check the need of requiring the switchgear manufacturer to design the breakers for an enhanced TRV test-duty T30 (30% of maximum short circuit rating). This is a possibility available in principle as general information in IEC reference standard for medium voltage and high voltage circuit breakers [5], but the final user or final customer shall require specifically this enhanced test-duty to the manufacturer since it is not included by-default in the switchgear design of medium voltage circuit breakers.

V. REFERENCES

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VI. APPENDIX

A. Electrical Network Component Data

TABLE A-I
HIGH VOLTAGE SUPPLY NETWORK

Equipment	Parameters
External supply grid at the point of common coupling of the industrial facility	110 kV rated voltage
	50 Hz rated frequency
	1600 MVA Max. 3-phase short circuit power
	8.4 kA Max. 3-phase sub-transient short circuit current at rated voltage
	X/R = 10 reactance to resistance ratio

TABLE A-II
DISTRIBUTION TRANSFORMER

Parameter	Numerical value
Winding arrangement	three-winding
Rated power	40 / 20 / 20 MVA
Rated voltage ratio	110 kV / 10.5 kV / 10.5 kV
Short Circuit impedance, referred to 40 MVA primary to secondary primary to tertiary secondary to tertiary	 Z_{12} = 20% Z_{13} = 20% Z_{23} = 37.6%
reactance to resistance ratio of transformer impedance	X/R = 50
10 kV winding capacitance to earth	1000 pF

TABLE A-III
MEDIUM VOLTAGE DISTRIBUTION SWITCHGEAR

Parameter	Numerical value
Rated operating voltage	10 kV
Rated insulation voltage	12 kV
Rated current	2500 A (air natural)
Short Circuit withstand Thermal withstand Breaking withstand Making withstand	 40 kA, 1 s 40 kA rms symmetrical 100 kA peak
Circuit breaker technology	Vacuum interrupter
Circuit breaker insulation voltage	17.5 kV
Transformer-limited fault special test-duty	T30 test-duty, Annex-F of IEC 62271-100
Reference design standard	IEC 62271

VII. VITA

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Mr. Paolo Marini received his Master of Electrical Engineering degree in 2005. In 2006 he joined the Department of Electrical Engineering of Tecnimont Company based in Milan, Italy. He is an Individual Member of the International Council on Large Electric Systems (CIGRE), an Individual Member of IEEE Industry Applications Society (IAS), and an Industrial Member of the Italian Electrotechnical Committee (CEI), Technical Sub-Committee SCT17 "HV Assemblies and Switching Devices".
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