Potential Risk of Failures in Switching EHV Shunt Reactors in Some One-and-a-half Breaker Scheme Substations

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***Abstract* – This paper reports the case of some EHV circuit-breaker repetitive failures during the opening of a 100 MVAR shunt reactor in a 400 kV substation in central part of Iran. By taking advantage of the simulation capabilities of EMTP-RV, the restructured version of the DCG-EMTP and its new GUI, major understanding of arc-circuit interaction phenomena was achieved. Simulation results show without any doubt that opposite-polarity high frequency arc-instability-dependant oscillations caused mainly by current transformers on each side of the breaker were responsible for its thermal failures and thus the non-interruption of the low 50 Hz reactor current by the 50 kA circuit-breaker.**

This paper represents a major contribution to the field of shunt reactor circuit-breaker applications. It is expected that large transient simulations with EMTP-RV incorporating circuit parameters frequency-dependency and dynamic arc modeling will contribute, in some cases, to a much safer shunt reactor installation.

Keywords – Shunt reactor, arc instability, circuit-breaker thermal failure, arc modeling, EMTP

I. Introduction

Switchable shunt reactors located on both line terminals and substation bus-bars are commonly used on long radial EHV transmission networks for the purpose of voltage control during daily/seasonal load variations. Extensive research and field tests have been performed by large utilities since the late 1960's in order to understand and thus control the severe and unique duties that are imposed on the breaker or on the load-break switches performing these tasks. Once in a while however, unexplained failures do occur in different parts of the world. At least two of such failures have occurred in a one-and-a-half breaker substation in Iran on 400 kV SF_6 circuit-breakers during the last 15 years. Since these breakers were supplied from two different manufacturers, design particularities and mechanical misfortunes were excluded as the reason behind these violent explosions. Consequently, electrical causes due to the interaction of the arc-circuit were investigated as a possible way to explain the repetitive nature of these failures.

The main objective of this paper is to report the major findings related to the in-depth investigations, which successfully resulted in the full understanding of the involved phenomena. Although the authors do not claim that the extremely complex arc-circuit interaction phenomenon may precisely be predicted yet by advanced simulation software, it is worthy to mention the major role that the usage of a new EMTP version [1] and its new powerful GUI [2] (called EMTP-RV and EMTPWorks respectively) have played in solving these complex problems.

II. Circuit-breaker failure history in Yazd-1

Yazd-1 is a major 400 kV substation in central part of Iran supplying the city of Yazd with two 200 MVA 400/63 kV transformers. Designed with a conventional one-and-a-half breaker substation scheme, it was commissioned in 1987 as a turnkey project supplied by a European sublicense manufacturer. Fig. 1 is created in EMTPWorks and depicts the details of this substation and the distances separating different equipments.

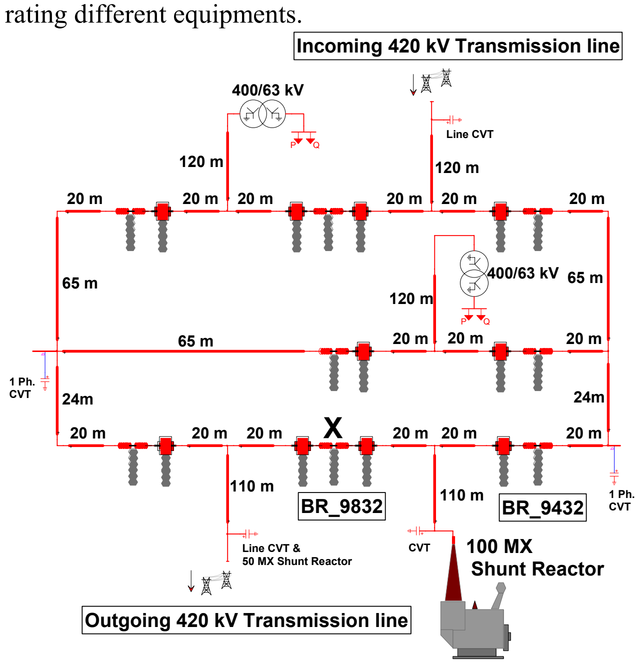

Fig. 1. Yazd-1 400/63 kV substation

The 100 MX shunt reactor is a three-phase five-leg-core type design protected with conventional SiC arrester. The original 400 kV circuit-breakers were of a SF_6 double-blast design from manufacturer A with two chambers in series each equipped with a 500 pF grading capacitor. Around 1992, the two shunt reactor circuit-breakers were replaced by a more conventional SF_6 type from manufacturer B with 1600 pF grading capacitors per chamber as a possible solution to the first couple of BR_9832 failures. The original current transformers (CT) had a rating of 150 VA with five cores on the top, three of which were used for protective purposes. Five out of six CT's of BR_9832 were also replaced by five cores 500 VA type from a different manufacturer for the same reason. Phase (c) at the right hand side of BR_9832 has the only old 150 VA CT.

Since 1987, circuit-breaker BR_9832, marked by a cross (X) in Fig. 1, has failed five times during the reactor opening on a single-phase. Three of such failures have occurred on phase (b) in static open position (type I) and due to operator mistakes by not opening the corresponding disconnects when BR_9432 was doing the final reactor interruption. The remaining two failures happened dynamically (type II) on phase (b) from manufacturer A and phase (a) from manufacturer B during the very few times BR_9832 had the role of final reactor interruption. Although the aim of this paper is to explain the reasons behind the failure of type II only, it is worthy to mention that investigations based on EMTP simulations have led to the following conclusion: single-phase CVT installed on the main bus-bars (phase b only) and the three-phase CVT at the reactor contributed to a higher than normal level of current chopping on the phase b of BR_9432 (about 25 A for a long arcing time) thus producing a voltage of around 3 pu (1pu is 326 kV crest) between the static open contacts of both the main and auxiliary (closing) chambers of phase (b) of breaker BR_9832. It is the authors opinion that the type I failures have occurred because the static withstand level of the auxiliary chamber stressed by a slow-front wave (50 and 700 Hz) is only around 2.4 pu. Post-failure inspections of all the three failures showed the extent of damages on the closing resistor blocks proving indeed that the arc was first established in the auxiliary chambers.

As for the two type II failures, since the minimum dynamic withstands level of the auxiliary chamber is believed to be around 3.6 pu during the first few crests, dielectric type failures were excluded. Moreover, no static type I failure of BR_9432 has ever occurred during the few times where BR_9832 was putting the reactor definitively out of service with BR_9432 in open position. Since shunt reactor interruption involves arc instability and the creation of relatively high di/dt's near current-zeros, circuit-breaker thermal failure, although never reported before for similar cases, was recognized as a lead justifying thus in-depth investigations based on detailed EMTP simulations.

III. Review of Circuit-Breaker Arc Instability During Shunt Reactor Opening

Considerable amount of information based on the pioneering work of [3][4] exist in the literature [5][6] about the phenomenon of arc instability or current chopping. Basically, the inverse V-I characteristic of the arc and its thermal inertia introduce some arc-voltage-proportional inductance and negative resistance within the circuit during current variations. Arc instability in circuit-breakers may occur only at high frequencies (few ten's up to hundred's of kHz) and near current-zeros (up to few ten's of A). As the 50-Hz-current-dependant variable DC arc voltage excites all the circuit natural frequencies, arc instability happens at the frequency (or the frequencies) where the amount of negative resistance introduced in series cancels out the total frequency-dependent resistance of the circuit, thus creating a negatively damped current oscillation in the form of $e^{-\alpha t}\cos(\omega t)$, α having a negative value. Since the arc introduces also some small variable inductances, negatively damped current oscillation may only happen at the frequency where the impedance seen by the arc (including the grading capacitor in parallel) presents a small capacitive value. Based on this reasoning, arc instability may only occur at the frequency which is slightly lower than the zero frequency of the impedance seen by the arc. If sustained, this growing-up current oscillation will eventually cross the zero value and depending on the di/dt involved (function of α and ω) the breaker may interrupt the current. A shunt reactor circuit-breaker is practically the only application prone to arc instability because both the reactor and the source impedances are shunted at high frequencies by the few nF's of natural/artificial capacitances (reactor, power transformer or CVT) on each side of the arc itself separated by only ten's of meters of bus-bars. Fig. 2 which corresponds to a typical EHV shunt reactor installation shows a main 260 kHz zero impedance is formed by C1, C2 and approximately 220 μH of inductance is seen by the arc. Arc instability may then occur in this circuit at a frequency lower than 260 kHz where the negative resistance introduced by the arc cancels out the frequency-dependant resistance of the 220 μH series inductance at this frequency. The problem however is not that simple to study analytically as there are usually some other CVT's and high power transformers with few nF of capacitance not far away on the source side of the breaker.

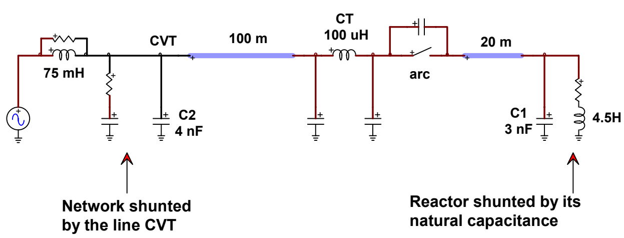

Fig. 2. Typical 735 kV shunt reactor installation

The overvoltage created at the reactor by the arc instability and the phenomenon of high dV/dt applied to the reactor due to circuit-breaker arc reignition are the two main concerns of utility engineers. The first is very much dependent to the value of the chopped current which itself is dependent to the involved breaker's type (arc voltage and V-I characteristic) and the circuit parameters. Although basically understood, arc-circuit interaction can not be precisely modeled because of the extremely non-linear behavior of the arc near current zero and the circuit frequency-dependant parameters. Consequently up to now, the overvoltage factor may only be estimated by the so-called circuit-breaker chopping number which have been reported practically in different installations to vary within the range of 15 to 20e04 for air-blast circuit-breakers, 7 to 10e04 for oil and 4 to 17e04 for SF_6 breakers [7]. It is the authors belief that the comparative large differences between the high and the low reported values of chopping number for SF_6 breakers, is an indication that arc-circuit interaction may play a more pronounce role on the arc instability of SF_6 breakers than of the two other types. This belief justified again to look more profoundly at the circuit surroundings of breaker BR_9832 at the Yazd-1 substation. Moreover, the fact that both double and single-blast puffer type SF_6 breakers from two different manufacturers have failed at the position BR_9832, suggests that the phenomenon involved is more dependant on the immediate surroundings of the breaker than the arc characteristics itself.

IV. EMTP-RV INVESTIGATION OF CIRCUIT-BREAKER FAILURES AT YAZD-1

A. Simulation method and parameters adjustment

EMTP-RV [1] has been used extensively for the modeling purposes. It offers several computational advantages such as high simulation speed, automatic memory allocation and a very large scale solver. Moreover the new EMTPWorks GUI [2] with mask and symbol editing capabilities facilitates the construction and handling of large simulation systems as the one reported here.

The whole substation as shown in Fig. 1 was modeled. Frequency-dependant models of bus-bars and lines were initially used. Later, frequency scan simulations showed indeed that the two 300 km 400 kV lines may be replaced conveniently with 350 ohm resistors without loosing any information higher than 30 kHz.

As ideal switch models cannot predict the chopping level and do not create the right di/dt with the specified current margin, the circuit-breaker under investigation was modeled according to a Cassie-Mayr [8] model by the use of a nonlinear resistance computed using the control library functions of EMTP-RV (Fig. 3).

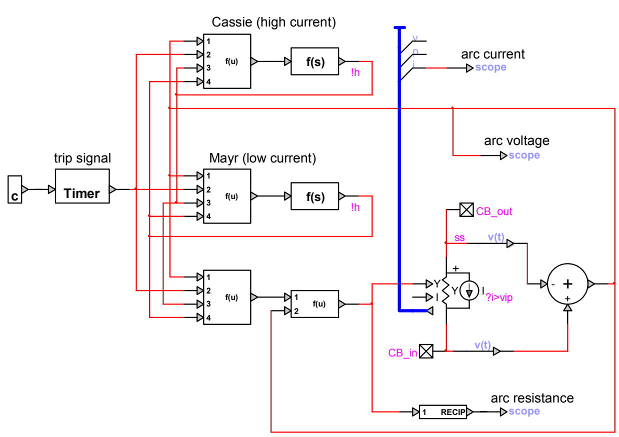

Fig. 3. Black-box arc modeling (Cassie-Mayr)

Arc current, voltage and resistance can be visualized by the scopes as shown. Cassie-Mayr arc parameters for both type of breakers were adjusted based on previous modeling experiences and checked for thermal capabilities under kilometric faults. Fig. 4 shows the thermal behavior of the breaker from manufacturer B with the Mayr cooling Power increased by 130% in order to take into account the effect of pressure increase due to the high short-circuit arc volume in the nozzle, which is not the case during the low shunt reactor current interruption. More sophisticated Mayr-modified arc models with additional empirical parameters were judged to be impractical in this study because of the lack of data and circuit frequency-dependant parameter uncertainties.

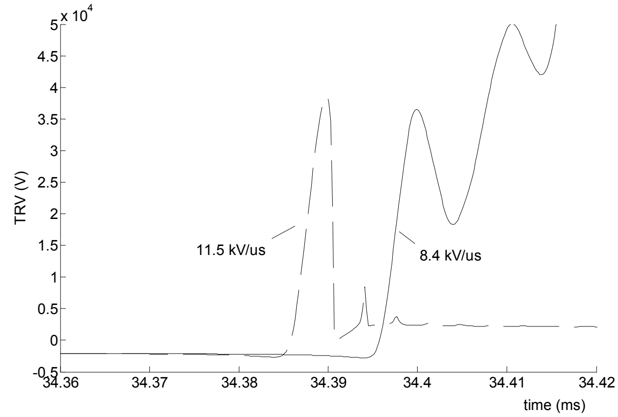

Fig. 4. Kilometric fault strength of the modeled arc (Clearing at 28.9 A/µs and failing at 31 A/µs)

Shunt reactor circuit-breakers have normally only one CT at their side. BR_9832 at Yazd-1 is equipped with one CT at each side because of the use of back-up protections (line and reactor protection each using a different CT) against faults at the breaker or its immediate surroundings. Although the influence of CT's and their high-frequency modeling have seldom been reported in the literature even for circuit-breaker reignition phenomena studies, they may introduce ten's of micro-henries in the circuit and must be taken into account. Based on the cores mean radius and the total cores cross-section area, the series inductance of the 150 and 500 VA CT's were estimated as 55 and 200 µH respectively. The CT's were modeled as in Fig. 2 except that some resistances were added to the circuit in order to take into account their high-frequency behavior. However as not so much is known about the CT's behavior at high frequencies, it is in the author's opinion that like the arc itself, CT modeling represents the other major weak point in trying to reproduce precisely the involved phenomenon in this study.

B. Impedances seen by the arc

The series of simulations reported here correspond to the last BR_9832 failure on phase (a) with the breaker from manufacturer B. The impedances versus frequency as seen by the arc of the circuit-breaker differ from one phase to the other since the bus-bars are not symmetrical and because of the presence of single-phase CVT's on phase (b) only and of 150 VA CT on phase (c) of BR_9832. Fig. 5 shows the characteristics of these impedances.

All the three phases present low first zero impedances around 81 kHz. This corresponds to the 97 kHz oscillation between the two main capacitances (CVT + reactor capacitance and line CVT) and about 660 µH of inductances (260 µH of bus-bar and 400 µH of CT). The 16 kHz reduction is due to the effect of the network connected to both left and right (throughout the 0.8 nF grading capacitor of BR_9432) sides of BR_9832. The second low value zero impedance happens around 400 kHz, but only on phase (a) and (c) and this is mainly due to the oscillations of the CT's with the rest. Finally, an approximate 7 kΩ 210 kHz main pole resonance is seen by all the phases of BR_9832.

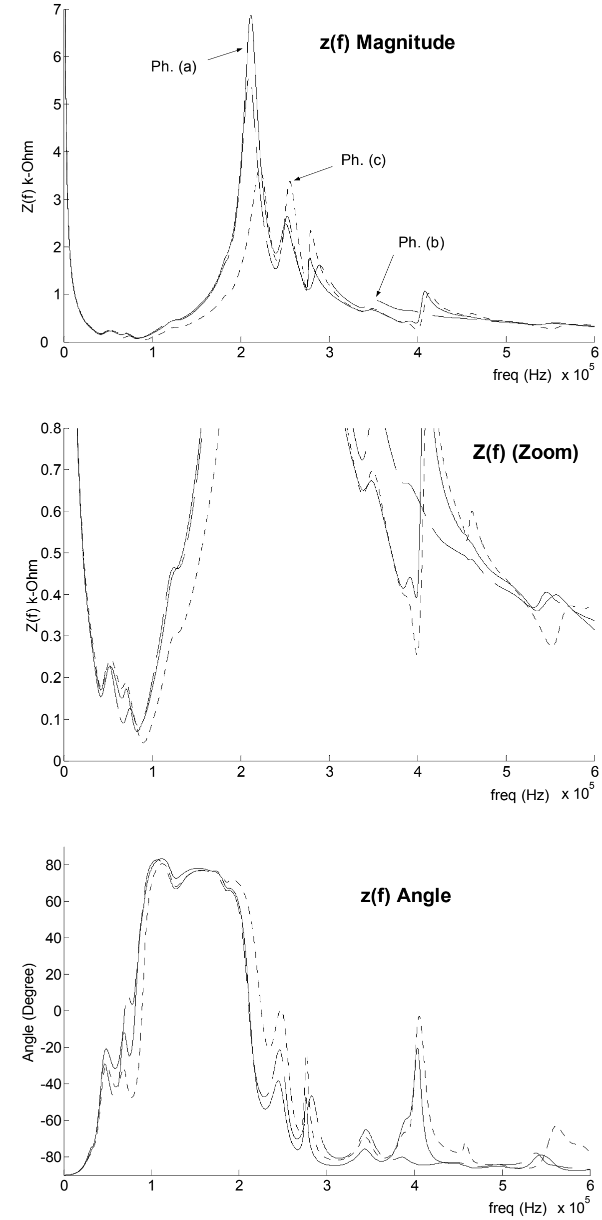

Fig. 5. Impedance characteristics as seen by the arc of BR-9832 circuit-breaker

C. Arc instability

With these remarks in mind, a time-domain simulation was performed with the described arc model in action on phase (a).

It is valuable to mention that a 2000 μs total simulation duration with a time-step of 5 ns took about 250 s of CPU time on a 1.2 GHz Pentium III laptop. This relative exceptional performance together with the ease of changing rapidly different circuit parameters with the GUI, permitted a large number of subsequent simulations during a day of work and represented a major factor to the successful achievements presented here.

Fig. 6 shows that an arc instability oscillation at 66 kHz with large negative damping produced a chopping current of 27 A. From Fig. 5, the series circuit with the arc presents some 140 Ω impedance with an angle of –18 degrees (capacitive) which means that a minimum of about 133 Ω of negative resistance was produced by the arc in the last current loop. This value seems reasonable since the arc resistance during this period varies extremely rapidly (from 102 Ω at 25 A to 1400 Ω at 5 A). Since the breaker is only very little stressed thermally at these di/dt (4.5 A/μs) and dV/dt (2.2 kV/μs) near current zero, by no means breaker failures can be imputed to this.

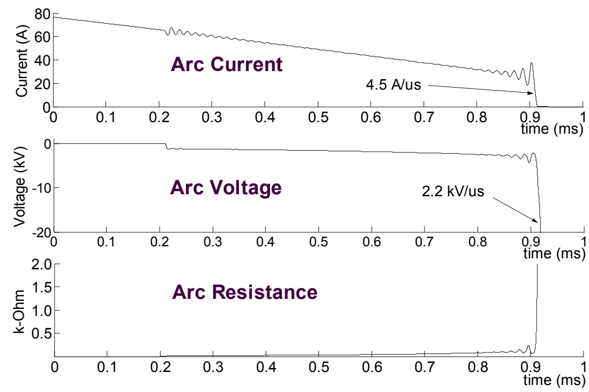

Fig. 6. 27 A chopped current by the modeled arc

The 27 A level of chopped current being a little bit high for these relative low frequency arc oscillations, attempts were made to find out more about it by decreasing slowly the cooling power of the arc. Although the level of chopping was decreased to 18 A, no special phenomenon was observed. The effort was then oriented to increase slowly the damping of the CT's at high frequencies and those of the circuit elements, especially those of the two power transformers and the 100 MX shunt reactor. The over hundred subsequent simulations finally paid off when an over-negatively damped current oscillation appeared in the circuit. Fig. 7 which corresponds to this surprising observation, shows that the 24 A chopped current produced by the arc-circuit interaction creates a suppression peak of about 0.81 pu across the breaker. Although a little bit high for SF_6 breakers, it is not the value of the suppression peak which is surprising. The surprise lies more closely near the current zero itself.

All the necessary information to explain definitively the BR_9832's dual failures in Yazd-1 is shown in Fig. 8.

Basically, lowly damped arc-circuit interaction at a relatively low frequency of 66 kHz excited a second simultaneous arc instability at a higher frequency in the last current loop before current zero. The current spike around the instant of 0.955 s corresponds to the instability created at around 400 kHz due the second low zero impedance nearby (Fig. 5). This second very brief high frequency arc instability excited by the rapidly falling arc resistance due to the additional loop of the 66 kHz instability creates a high di/dt (14.5 $\mathrm{A}/\mu\mathrm{s}$) near current zero. The dynamic arc resistance trajectory of Fig. 9 demonstrates that a negative 500 Ω resistance is very much present in the circuit for a short period of time.

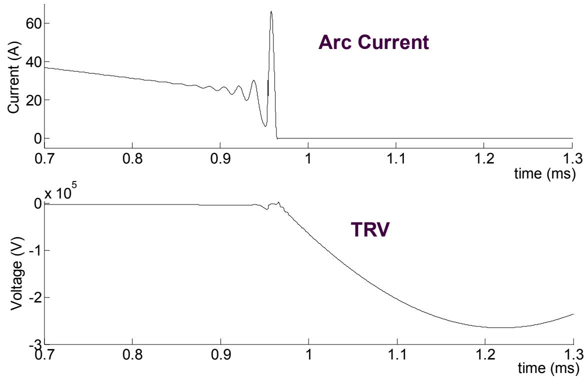

Fig. 7. 24 A chopped current produced by an over-negatively damped arc oscillation

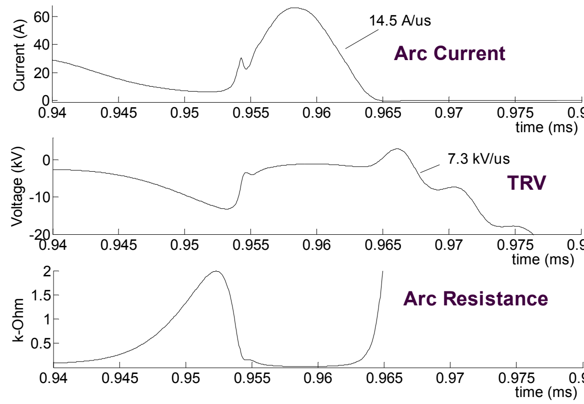

Fig. 8. Zoomed view of Fig. 7 near current zero

The injected di/dt then excites the 210 kHz parallel resonance seen across the breaker thus creating a high dV/dt of 7.3 $\mathrm{kV}/\mu\mathrm{s}$. The fact that the arc produces a 0.4 A post-arc current after the current zero is another indication that indeed the breaker is stressed thermally by these phenomena. In the author's opinion, a slight increase of the arc instability current near 400 kHz may easily double the mentioned current and voltage derivatives near current zero.

The example of Fig. 10 shows a much more serious situation. The shown di/dt and dV/dt correspond to a simplified circuit (only with CT's, 130 m bus-bars and the 2 capacitances with an equivalent source) with less damping but with about 50% more cooling power. The second zero impedance in the simplified circuit occurs at about 550 kHz but the 210 kHz pole remains the same.

It should be noted of course that the authors do not claim to have reproduced closely the stresses resulting to the last BR_9832 failure. Too much inexact but reasonable parameters are involved in the performed simulations. The authors do claim however that they have demonstrated for the first time by advanced EMTP-RV simulations that thermal failure of shunt reactor circuit-breakers is a reality under certain circuit conditions. Although rare, the circuit-breaker in these cases must face kilometric line fault-like conditions without having the same pressure increase in the nozzle due to a high short-circuit current arc.

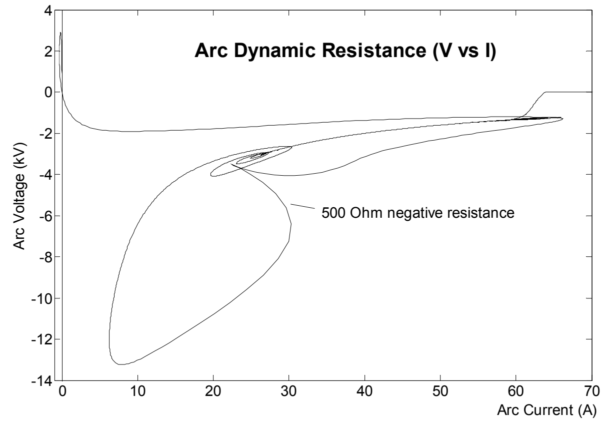

Fig. 9. Arc dynamic resistance trajectory

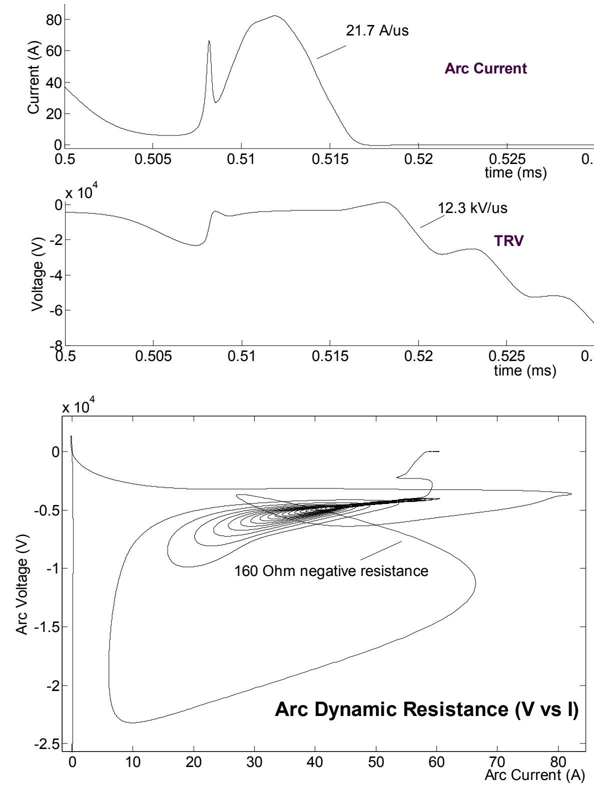

Fig. 10. More pronounced second-frequency arc instability

To complete the picture, Fig. 11 shows the voltage oscillation on each side of the breaker after the second current zero corresponding to the post-arc current extinction. Both voltage oscillations happen at a main frequency of 210 kHz but in opposite polarity because of the almost identical symmetrical arrangements of the CT's, 130 m bus-bars and the line CVT and reactor's CVT and capacitance on each side of the BR_9832 breaker; the two CT's of course playing the major role in them. Consequently, the breaker, without being in a short-circuit condition, must face near current zero, the current and voltage stresses relative to almost two simultaneous kilometric line faults, one at each of its sides.

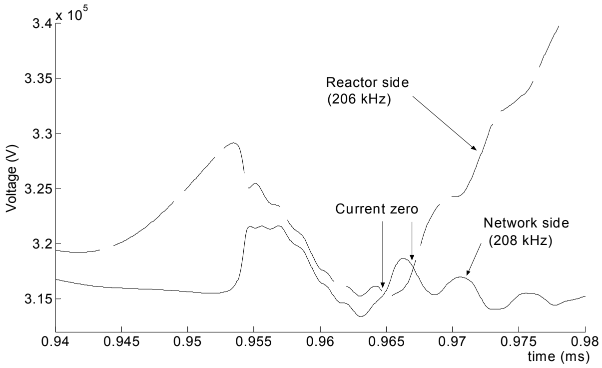

Fig. 11. High frequency voltage oscillation on each side of the circuit-breaker

Finally, Fig. 12 compares the magnitudes of the impedance versus frequency for the two networks seen by the arc of phase (a), producing the two different current chopping behaviors presented in Fig. 6 and Fig. 7 respectively.

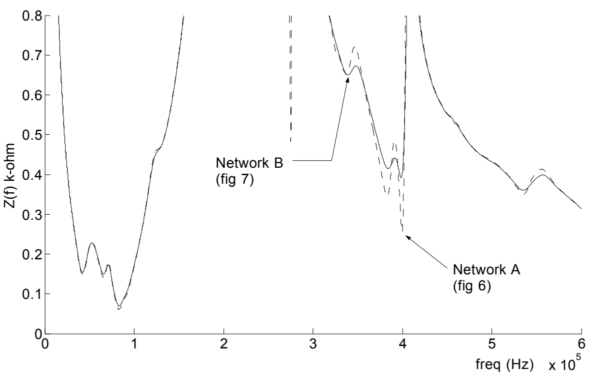

Fig. 12 Impedance vs. frequency seen by the arc in the two studied networks

The fact that a more damped network is creating a worse situation needs some explanations. It is obvious that the 66 kHz oscillation is excited first because of its lower zero impedance value. As stated and shown, it is the arc current oscillation at 66 kHz which may excite the 400 kHz arc instability. The impedances seen by the arc in Networks A and B are 140 and 150 Ω respectively, both with an angle of –18 degrees. It is indeed this 10 Ω additional resistance to be conquered in network B by the negative resistance of the arc that pushed the oscillatory arc current of Fig. 6 to go through an additional loop and create the arc current of Fig. 7. Without this, the rapid falling of the arc resistance of Fig. 8 could not occur and thus there was no 500 Ω negative resistance to cancel out and consequently excite the arc instability at 400 kHz, even though there is less resistance to be cancelled in the network A.

V. CONCLUSIONS

Unexplained dual failures of a particular breaker in a 400 kV one-and-a-half breaker substation in Iran oriented special efforts to an in-depth EMTP-RV study of the arc-circuit interaction. Results show that a double-frequency arc instability at 66 kHz and 400 kHz was responsible for the creation of high di/dt stresses around current zero. Symmetrical arrangement of CT's, long bus-bars and CVT'S in the immediate surrounding of the shunt reactor circuit-breaker then created opposite-polarity 200 kHz voltage oscillations with high dV/dt's resulting to the thermal failure of the circuit-breaker.

Shunt reactor installations with the circuit-breaker located far away from the reactor and the substation main bus-bar or having one large CT at each of its sides need to be looked at closely. Although precise modeling of high frequency damping playing an important role is quite difficult, frequency scans and time domain EMTP-RV simulations with dynamic arc modeling, may contribute to predict the risks associated with this type of installations.

ACKNOWLEDGMENTS

The authors would like to acknowledge the contributions of Dr. S. Montasser Kouhsari from the Tehran Polytechnic University and of Mr. F. Jahanbakhsh from Tavanir Power Corporation.

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