Ferroresonances during Black Starts - Criterion for Feasibility of Scenarios

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Abstract --After large black-out events in the USA and Europe, there is a great interest to have power systems able to restart as quickly as possible, systems with reasonable number of potential starting sources and sufficient variety of black-start scenarios.

Typically, recovery of a system operation starts from small generator(s), which power should be given to a remote larger power plant to start up it. During this process, various nonstandard combinations of sources, lines and transformers can occur, that can be unstable and exhibit very high level of transient temporary overvoltages. The main cause of that is a ferroresonant oscillation between source, line capacity and switched power transformers with saturation. The transient behaviour with temporary overvoltages can endanger hv equipment and it was considered that surge arresters are the most sensitive. Therefore a criterion of satisfactorily low and permissible thermal stressing of surge arresters was established as the criterion for acceptability of a given step of black-start process.

The problem is in the paper demonstrated on the real event - black-start experiment realized in czech power system. The ferroresonance was predict by EMTP simulation during preparation of the test and it really occured.

The authors analysed various configurations of sources, lines and transformers by EMTP simulations on appropriate EMTP models and prooved them for transient ferroresonance - its magnitude and duration. They looked for some rules for appearing of resonances and temporary overvoltages and found some regularity, which will be presented in the paper. Then the authors created models of real network configurations for black-starts and prooved them by simulation. Permissible black-start scenarios were specified on basis of the criterion of acceptable energy absorption of surge arresters then verified as feasible and implemented to plans of system recovery.

Keywords: Ferroresonance, magnetizing curve, blackstart scenarios, temporary overvoltage, transient phenomenon.

I. INTRODUCTION

After quite long period without any black-outs and relatively continuous delivery of electric energy lasting in Czech Republic maybe 20 years now we face to more often occurrence of nonstandard events in the system resulting in partial outages, avalanche outages, islanding e.t.c., . There are many reasons for that, one of them is rapidly increasing amount of transmissed electric energy throughout the networks that also changes traditional directions of transmission.

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Total large blackout is the worst-case event and it is very rare but possible as we know from events of recent years (14.8.2003 - USA and Canada, 23.9.2003 – Sweden, 28.9.2003 - Italy, 12.7.2004 – Greece, narrowly avoided 4.11. 2006 in West Europe).

Nowdays, network operators in Europe should be prepared to such events and they should be able to restart systems after large blackouts. Due to variety of situations after blackouts, operator should have prepared variety of scenarios how to regenerate the system. There are generally two alternatives: restoring with help of neighbouring or remote healthy network or restoring from own sources able to start independently on external delivery. In the second case, typical blackstart source is hydro generator of small or middle power. The power of such generator should be given to a remote bigger power plant auxiliary enabling to start this power plant and so step by step to enlarge the island. Typical start configuration we can see in figure 1.

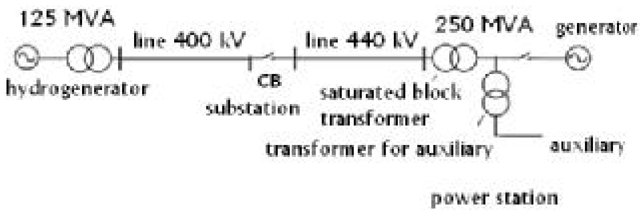

Fig.1 Typical configuration for blackstart

Here the voltage from water power plant is given via line A 400 kV to separated bus in the substation, where path via line B 400 kV to large power station is prepared. After closing of circuit breaker CB, a transient phenomenon appears thanks to saturation of block transformer.

II. TEST OF BLACKSTART - REAL NETWORK EXPERIMENT

In autumn 2004 CEPS - Czech transmission operator tested an experimental start from dark of nuclear power plant Dukovany. Its 4. block should have to be started from near water-pump power plant Dalesice, the scheme is in figure 2.

Voltage from hydrogenerator- block transformer EDA HG3 was via line V482 2,3 km long given to bus 400 kV in substation Slavetice. Then CB in the substation Slavetice should connect two parallel block transformers in Dukovany via line V486 3,7 km long. Before realisation of the experiment, some calculations were performed on a model of the configuration in EMTP.

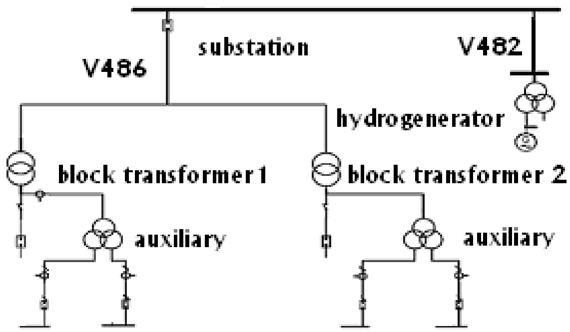

Fig. 2 Scheme of blackstart configuration tested in real network

Simulations of switching showed quite high level of transient ferroresonance overvoltages with overvoltage factor 1,7 lasting more than 20 seconds. Because of there are surge arresters 400 kV installed in both power station and in substation too, absorbed energies were tested by simulations and it was created ad hoc criterium for prepared test: If the transient will last more than 20 s after switching on, the experiment must be immediately interrupted, otherwise the surge arresters will be thermally overloaded! The magnitude of the temporary overvoltage reach such values that it initializes protective effect of MOAs. Their current of order Amps with their thermal effects can degrade blocks totally or - what is maybe worse - only partialy - their total failure is then postponed to near or farer future.

There exist records of overvoltage transients obtained during experimental black-start tests - a part of record is in figure 3, where transient is recorded in scale of phase-to-phase voltage. Dangerous ferroresonance reaching maximally overvoltage factor 1,8 lasted 15 second . The experiment went through succesfully without interruption, but very narrowly and it was clear, that for next, everything must be better under control and with better safety margine. So it was starting poin for analysis, only part of its results is presented here.

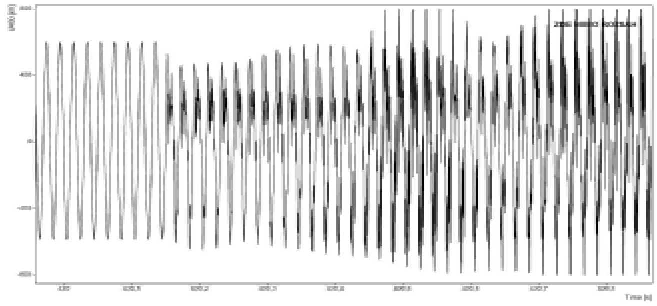

Fig.3 Part of the record of the overvoltage transient during blacstart test

III. Circuit parameter analysis

Transient behavior during energization of big block transformer from small generator is influenced by following parameters:

- source impedance
- capacity of lines given by their conductor configuration and their length
- magnetisation curve of energized block transformer
- time of switching relating to sinus of voltage and time sequence of CB poles

A. Influence of magnetizing curve

Shape of magnetizing curve and saturation knee position determines a magnitude of inrush currents of energized block transformer. Lower knee implies more probable ferroresonance with longer time duration.This is important if there is more than one transformer that can be chosen for black start. The transformer with smaller inrush currents should be used. An apropriate model of energized transformer is the key element of the model. Its magnetization curve was created with help of records from real measurements of inrush currents during energization of the given transformer from a low impedance network. The model was verified by comparison of records with simulated energization by the same way - it seems to be the best way, how to be close to reality.

B. Influence of CBs sequence and time of switching

Magnitude of inrush currents is influenced by the time instant of switching relating to voltage sinus and by a sequence of CB poles. If the CB is not equipped by synchroswitch the time of switching is accidental.

Maximum inrush current appears, if switching-on of the first switched phase happens round voltage zero. It would be considered to use CB with synchroswitch control in case of important configurations for blackstart. Such CB can be tuned to optimum switching minimizing inrush currents of transformer almost to zero. Then blackstart transient should be also favourably lower but it must be verified case to case. The question is a repeatability of such CB synchro switching regarding pre-strikes of CB. Analysis presented in paragraph 3.3 showed a lower influence of closing sequence to ferroresonance than it was supposed.

C. Influence of line length and source inductance

Basic configuration of build-up trace consists of generator, block transformer, hv line and switched on transformer in remote power plant. The line represents a capacitance, which creates with inductance of the generator, the block transformer (its stray inductance) and with switched on remote transformer LC circuit. The switched on transformer saturates and ferroresonance can appear. It is accompanied by temporary overvoltage, that can cause a damage of surge arresters. Ferroresonance is influenced mainly by inductance of source and by capacitance of the line. But thanks to nonlinearity of the phenomenon, it is not possible simply to state resonance from LC parameters. Therefore a detailed analysis was performed with help of large set of simulations in EMTP for basic configurations, when influence of circuit parameters was studied and apearing of ferroresonance was tested.

Two model transformers Trafo H and Trafo L with two differnt magnetizing curves were switched on.

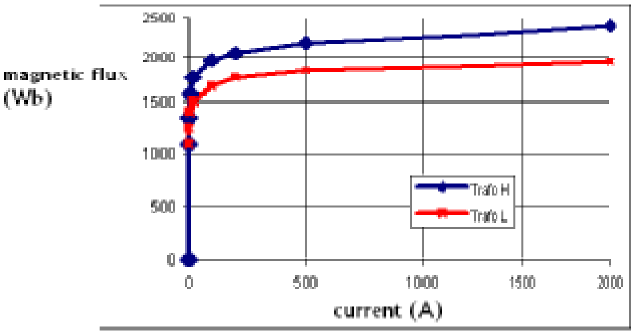

Fig. 4 Magnetizing curves of transformer models for simulations

CB sequence

To be closer to the worst case, CB sequence was chosen on base of analysis with results summarized in the table 1.

TABLE I
INRUSH CURRENTS FOR VARIOUS SEQUENCES OF POLES AND TIME TO SINUS

X = 20 ohm I_{1k} = 12 kA	Sequence (sinus angle/times of poles in ms)			
	0/100-100-100	30 /10-10-10	90 / 100-97-102	105/100-97-102
Trafo H	90	220	815	1000
Trafo L	700	1300	2500	2850

The second worse sequence was chosen for simulations: 90 / 100-97-102.

Source impedance

More powered generator has usualy less source inductance. Simulations were performed for source inductances 450, 600, 800, 1000, 1200 a 1600 mH (recalculated for 400 kV). Corresponding power of generators is in the range 100 to 440 MVA. Stray inductance of the source block transformer 200 mH was added to the source impedance.

Length of lines

Length of line was changed in the total range from several km to 300 km but case to case in very fine steps, when border between ferroresonance and stable state was looked for. It must be noticed, that the obtained results are valid only for line 400 kV with conductor configuration of tower Portal.

Test criterion - exceeding of thermal capacity of surge arresters with energy absorption more than 1000 kJ - with some safty margin - was established for acceptance or forbiddance of tested blackstart configuration.

Evaluation of more than 1000 calculation brings graph in figure 5, that demonstrates dependance of ferroresonance (dark areas - trafo H - narrower zones and trafo L wider zones) on two parameters: source inductance (axis Y) and length of line (axis X) . It can be seen that dark zones create band of first, second and third resonances of configurations with stable white zones in between.

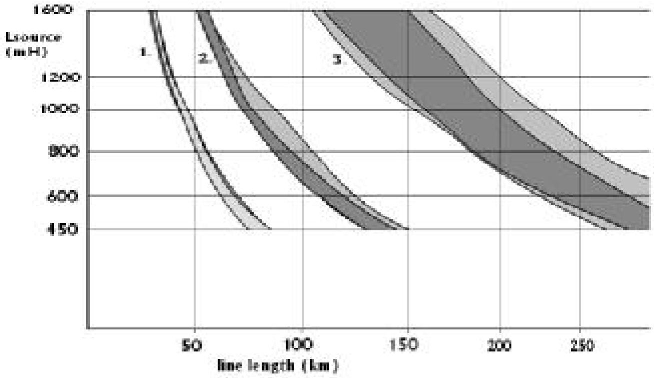

Fig. 5 Resonance ranges with exceeding of thermal capacity of surge arresters - trafo H (narrower zones) and L (wider zones), axis Y - source inductance, axis X - length of line 400 kV

As it can be seen from graph in figure 5, there is no big difference of results between trafo H and trafo L. Additional calculations showed, that ferroresonances in dark zones arise for wide variety of CB sequencies, so the influence of CB sequence is not so significant as it was supposed.

D. Explanation of 1.,2. and 3. resonance on an one phase model

For better understanding of resonant behaviour, 1-phase model of the same circuit with 1 phase saturated transformer was created. The voltage and current time shapes were compared for circuits with source inductance 650 mH but for various lengths of line falling to 1., 2. and 3. resonant range and to non-resonant range according to graph in figure 5. Scheme of the ATP model is in figure 6. Typical envelope of the inrush current between transformer and line is in figure 7a (black) and between source and line (red), zoom is in figure 7 b).

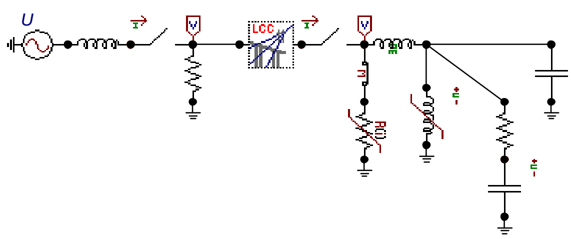

Fig. 6 Scheme of the black-start circuit

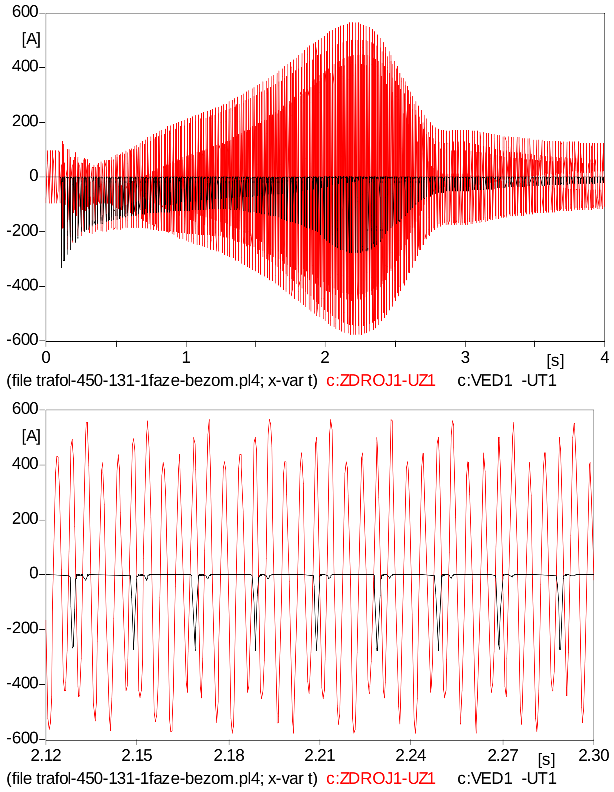

Fig. 7 Current envelope and zoom

Typical voltage envelopes are in figure 8 - resonant (red) and nonresonant (green).

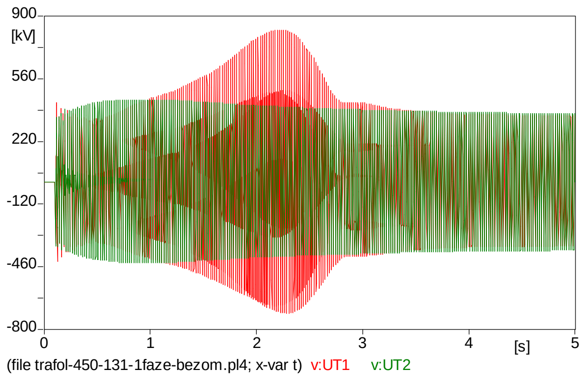

Fig. 8 Typical voltage envelopes, resonant- red nonresonant - green

Following figures show detailed resonant voltages comparing with nonresonant voltage of 50 Hz for three resonant bands. Figure 9a shows 1.resonance for 450 mH and line 63 km long - it oscillates on harmonic resonant frequency fr1 = 300 Hz, figure 9 b 2. resonance for 650 mH and line 124 km long fr2 = 200 Hz and figure 9 c) 3. resonance for a line 210 km long fr3 = 150 Hz. These frequencies are very aproximately linear resonant frequencies of LC circuit created by source inductance and capacitance of the line. The circuit is excited to resonance oscilations by nonlinear inrush current of the transformer as can be seen from figure 7 b.

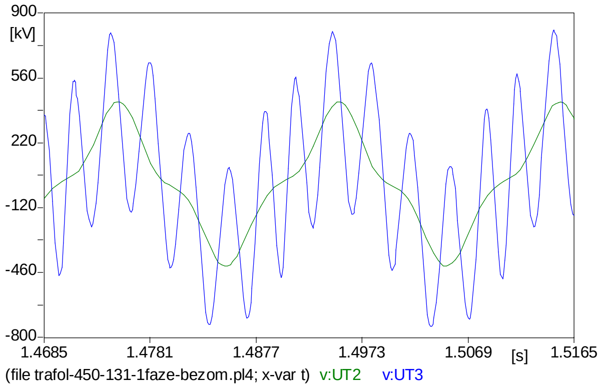

Fig. 9 a) 1st resonance fr1 = 300 Hz

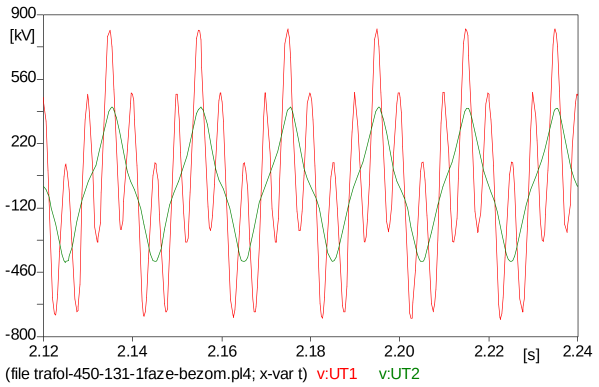

Fig. 9 b) 2st resonance fr2 = 200 Hz

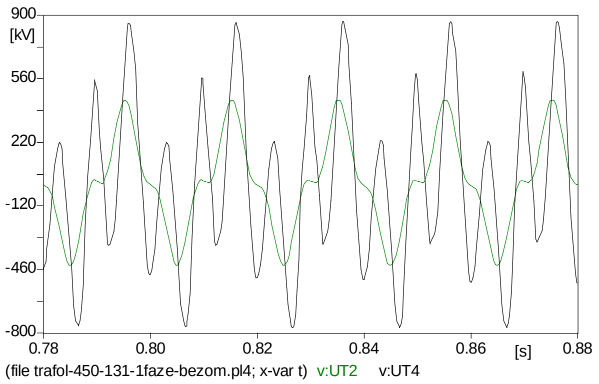

Fig. 9 c) 3st resonance fr3 = 150 Hz

IV. Conclusion

It was prooved by experiment and by EMTP calculations that improperly arranged blackstart scenarios can cause damage of hv equipment by transient ferroresonance overvoltage, surge arresters are the most sensitive. The feasible blackstart scenarios can be designed with help of careful analysis and EMTP simulations.

Inductance of blackstart source and length of line were found as the decesive parameters for origin of ferroresonance in given configuration. It was found that magnetizing curve and switching sequence of CB have less importance. Shunt reactors can help but simulation of cases is recommended.

V. References

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VI. Biography

Lubomir Kocis was born in Prague in 1952, he received the Ing. degree (M.Sc.) in electrical engineering from Czech Technical University Prague in 1975. He joined EGU HV Laboratory in 1978.
From 1984 to 1989 he worked on projects dealing with HEMP (High altitude Electromagnetic Pulse), especially on problems of generating and measuring of very fast impulses of voltage and electromagnetic fileld. He was co-designer of large outdoor HEMP simulator for testing of mobile electronic systems. In 1987 he joined WG 1 SC77C IEC dealing with HEMP effects in civilian sector.
Since 1989 he has been engaged in EMC hardening problems of electronic systems, RFI and TVI sources and their locating on lines and in substations. In the end of 80s he developed UHF locator of RFI wich was later modified and succesfully used for indication of PDs in HV apparatus (especially surge arresters and current transformers) on-line in substations.
In 90s, he has been technically responsible for many projects contracted by Czech Power Utility, including HV current transformer diagnostics, experimental and EMTP studies of overvoltage transients in transmission network and insulation coordination of overhead lines and substations. Many experimental results on one side and routine usage of ATP-EMTP for numerical modeling on the other side determined him to work on studies of specific problems of insulation coordination. He is member of CIGRE C 4.301 and D1.33.