Inductive load switching
Standardization status

Rene Smeets
KEMA Testing, Inspections and Certification
The Netherlands
Member IEC MT 32 (inductive load switching)


- Covers all voltage levels 1 – 800 kV
  - Unloaded transformer switching (no testing)
  - Motor switching ≤ 17.5 kV
  - Shunt reactor switching ≥ 52 kV

- Relevant for medium voltage: motor switching
  - Test-circuit defined in great detail
  - Three-phase interaction essential
  - High-frequency phenomena are represented
**IEC Test circuit for motor switching**

- **Source**: $U_r$
- **Bus representation**
- **Switchgear under test**
- **Cable**
- **Motor substitute**

- **Busbar 5-7 m allowing inductive coupling between phases**
- **Supply side capacitance**
  - 30 - 50 nF supply circuit A
  - 1.5 – 2 μF supply circuit B
- **100 m screened cable**

- **Motor model**
  - 10 – 15 kHz oscillating circuit power factor ≤ 0.2 or actual motor

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**Required tests**

<table>
<thead>
<tr>
<th>Test duty</th>
<th>Current</th>
<th>Capacitance</th>
<th>Nr. of tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100 A</td>
<td>30 - 50 nF</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>300 A</td>
<td>30 - 50 nF</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>100 A</td>
<td>1.5 – 2 μF</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>300 A</td>
<td>1.5 – 2 μF</td>
<td>20</td>
</tr>
</tbody>
</table>

**20 test at 0.5 ms steps of arcing time (at 50 Hz)**

**80 tests all together**
Example of 12 kV VCB (1) + arrester

Motor switching test-duty 2, 300 A, no re-ignition

- 44% of tests with minor chopping overvoltages only
- max. 3.5 pu (34 kV) across CB

Voltage across CB (pu) vs. arcing time (ms)

Highest level, voltage increased by current chopping
Minimum level without current chopping

Scale: voltage in kV, current A/10

Phase 1

Phase 2

Phase 3

Max. voltage across CB
12 kV VCB (2): Multiple re-ignition

Motor switching test-duty 2, 300 A, multiple re-ignition

12 kV VCB (3): MR + virtual chopping

TRV to 97 kV in 12 kV system = 10 pu
virtual current chopping at 237 A
multiple re-ignition

Motor switching test-duty 2, 300 A, multiple re-ignition and virtual current chopping generating huge overvoltage
- 56% of tests have multiple re-ignition, often followed by virtual current chopping
- max. 9.9 pu (97 kV) across CB
- TD 2 most severe: larger current allows larger virtual chopping
- Large supply side capacitance (TD3, 4) reduces transients
- Load voltage limited by arrester in CB

### 12 kV VCB (3): MR + virtual chopping

- Load side voltages limited by arrester
- 3.4 pu max voltage at virtual chop
Conclusions / remarks

- Current chopping is no problem
- Multiple re-ignition generate steep surges that may endanger winding
- Virtual chopping is common but can be dealt with by arrester
- Overvoltages in test-circuits are expected to be higher than in service
- There is no limit of overvoltages set in the IEC standard
- Only outside flash-over would prevent VCB from passing motor switching test
- IEC standard not adapted to VCB application

Future standardization in IEC

- New edition of IEC 62271-110 (inductive load switching) in 2013
- Shunt reactor switching re-introduced also in voltage range 12 – 52 kV

<table>
<thead>
<tr>
<th>Test duty</th>
<th>Nr. of breaking operations</th>
<th>current</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3 phase</td>
<td>1 phase</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
<td>18</td>
</tr>
</tbody>
</table>

- Short-circuit duties T10 & T30 will cover provided that their TRV covers inductive load TRV
- Criterion to pass: re-ignitions at one current zero only
frequent re-ignition no longer allowed

Market penetration of vacuum switchgear
End sheet

Thank you for your attention.
Transient Processes at Vacuum Circuit Breaker Switchings and Development of Technical Requirements for 6–35 kV Vacuum Circuit Breakers

Artem Bazavluk
Senior Engineer of Research Department
LLC BOLD, Novosibirsk, Russia
Damages at VCB switchings

Motors
XLPE-cables and terminals
Transformers
Current-Limiting Reactors

Transient processes at 35 kV VCB switching

Distance between B and C poles is 165 mm
Phase(B)–to–phase(C) voltage is 120 kV
- Damage of 35 kV VCB (Koksovaya Substation, Nizhny Tagil Steel Plant)

- Damage of cable terminal at 35 kV VCB switching (Koksovaya Substation, Nizhny Tagil Steel Plant)
Transient processes at 12.5 MW motor switching

Damage of current limiting reactor at VCB closing
Measuring Equipment of LLC BOLID

Up-to-date measuring equipment and own-constructed devices allow recording transient processes with high sampling rate in the broad range of time.

Overvoltages at VCB switchings

- Overvoltages due to current chopping
- Overvoltage escalation with high-frequency restrikes at VCB opening
- Overvoltage escalation with high-frequency prestrikes at VCB closing
- Overvoltages due to virtual current chopping
Current chopping and overvoltage limitation by overvoltage suppressors

$I_{\text{chop}} = 2.7 \ldots 5.0 \text{ A}$

Overvoltage escalation with high-frequency restrikes at VCB opening in the 10–kV network

$K = 5.75 \text{ p.u.}$

$n = 23$

$U_{\text{chop}} = 93.5 \text{ kV (9.64 p.u.)}$
Multiple restrikes due to contact bouncing at VCB closing

High-frequency overvoltages with prestrikes at VCB closing
Growth of defects in XLPE cable insulation under the application of high-frequency voltage

When suddenly injecting energy into solid dielectric material, bond rupture between molecules of carbon and hydrogen in points of higher electric strength \( E \) occurs.

Dependence of electric strength \( E_{\text{max}} \) at the end of the needle electrode corresponding to the beginning of water treeing growth on the frequency \( f \) for XLPE insulation.

Treeing growth in XLPE cable insulation

Water treeing "butterfly"-type which grows in insulation depth with the center in the point of local inhomogeneity.

Water treeing "fantail"-type which grows from the needle-type edge on the semiconducting screen.
Contact closure velocity versus time for various VCBs

- Russian circuit breakers
- Foreign circuit breakers

Vacuum Interrupter characteristics:
- Chopping current
- Material of contacts
- Degree of purity for contact surface
- Electric strength of contact gap
- Geometrical parameters of contacts
- Vacuum level
- Transient resistance of contacts

VCB Mechanism characteristics:
- Travel velocity of moving contact in the vacuum interrupter at closing/opening
- Contact bouncing
- Nonsimultaneous contact closing/opening

Technical characteristics for VCB to revise and introduce into normative documents:
- The rate of breakdown voltage (at VCB closing/opening)
- Travel velocity of moving contact (at VCB closing/opening)
- Electric strength at the distance of 2mm between contacts
  (Corona discharges inside a vacuum interrupter are inadmissible)
- Contact bouncing
- Chopping current
- Nonsimultaneous closing/opening
- Pressure inside a vacuum interrupter
- Transient resistance for vacuum interrupter contacts
Vacuum circuit breakers should be carefully verified and monitored by both manufacturers and operating companies.

Vacuum circuit breakers should be equipped with a special device for controlling and checking of their mechanical characteristics.

VCB characteristics should be periodically checked during their operation.

Switched equipment should be protected by overvoltage suppressors and RC-circuits (i.e. valid choice of VCB and devices for their protection depending on consumer loads).

XLPE cables, motors and transformers should switched by vacuum circuit breakers with higher technical requirements.

GOST requirements should not be applied for all types of vacuum circuit breakers. New power engineering equipment calls for additional requirements and strengthens existing requirements.

Conclusions

Thank you for your attention!
Recovering of electric strength in different mediums

Recovering of electric strength for 6mm gap after 1600 A interruption in vacuum and various gases under atmospheric pressure.
Overvoltages generated by VCBs
Basics of Inductive Switching

Overview

- **Breaking** of inductive currents
  - Chopping of current and associated over-voltage
  - Over-voltage produced by multiple re-ignitions

- **Making** of inductive currents
  - High-frequency making current
  - Pre-ignitions and associated over-voltage

- **Virtual** chopping

- Mitigation means
Chopping of inductive currents
Transient recovery voltage (TRV)

- After opening, current ceases just before current-zero at a level of 2 - 3 A (CuCr) (Chopping)
- Trapped current through $L_0$ charges $C_0$ >> $I_{chop}$ determines over-voltage
- This effect excites an oscillation of $L_0$ and $C_0$
  - Frequency > 500 Hz depending on $L_0$ and $C_0$
  - Determines the TRV steepness
- After current-zero, the charge in $C_0$ still can only discharge through $L_0$

$$U_{max} = \frac{L_0}{C_0} \cdot i_{chop} \quad f = \frac{1}{2\pi \sqrt{L_0 C_0}}$$

Breaking of inductive currents with short arcing time
Multiple reignitions during opening

1. After separation of contacts, current chops
2. Energy is trapped in the oscillatory circuit of the load ($L_0 - C_0$)
   The voltage at the transformer builds up
3. When TRV voltage across the contacts exceeds the dielectric withstand (short gap), the arc re-ignites
4. Vacuum interrupters are able to interrupt these high frequency currents with a steepness of up to 200 A/µs!
5. TRV builds up again, until the next breakdown occurs
6. The process continues, until the dielectric withstand between the contacts exceeds the TRV >>> multiple re-ignitions

Points 1 – 3 occur for every switching device, points 4 - 6 are specific for vacuum interrupters
Range of inductive currents and TRV values

<table>
<thead>
<tr>
<th>Transformer power</th>
<th>Primary inductance</th>
<th>Inductive current</th>
<th>Rate of voltage rise</th>
<th>TRV frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 – 2 MVA no-load</td>
<td>50 – 1000 H</td>
<td>0.1 - 1 A</td>
<td>&lt; 50 V/µs</td>
<td>&lt; 0.5 kHz</td>
</tr>
<tr>
<td>5 – 20 MVA no-load</td>
<td>5 – 20 H</td>
<td>2 - 10 A</td>
<td>&gt; 100 V/µs</td>
<td>&gt; 1 kHz</td>
</tr>
<tr>
<td>400 kVA induct. load</td>
<td>~ 1 H</td>
<td>~ 20 A</td>
<td>0.5 - 2 kV/µs</td>
<td>4 kHz</td>
</tr>
<tr>
<td>10 MVA short-circuit</td>
<td>3 mH</td>
<td>6 kA</td>
<td>4 kV/µs</td>
<td>40 kHz</td>
</tr>
</tbody>
</table>

Voltage rise with VI contact stroke: 30 to 60 V/µs
Voltage withstand at small strokes: 20 to 40 kV/mm

Making of inductive currents
High-frequency inrush currents

- After contact making, the charge on the cable capacitance \( C_z \) discharges into \( C_0 \) via the cable inductances \( L_{p1} \) and \( L_{p2} \)
  - Frequency of > 400 kHz
  - Similar to the switching of very small back-to-back capacitors
- In addition the inrush current of the transformer flows, however, on a 50 Hz time scale (10 – 12 x rated current)

\[
\hat{I}_{ce} = \Delta \hat{U}_c \cdot \frac{C_0}{L_{p1}}
\]

\[
f_{ce} \approx \frac{1}{2\pi} \cdot \frac{1}{\sqrt{C_0 \cdot L_{p1}}}
\]

for \( C_z >> C_0 \) and \( L_{p1} >> L_{p2} \)

\( C_0 \) consists of the capacitance of the load-side connection, but also of any earth capacitance of the transformer
Making of inductive currents
Multiple re-ignitions during closing

1. Before mechanical touch of contacts, a pre-ignition occurs at small contact gap
2. The source-side cable capacitance instantaneously charges the load-side capacitance \( C_0 \) and a high-frequency current flows
3. Vacuum interrupters are able to interrupt these high frequency currents with a steepness of up to 200 A/\( \mu \)s!
4. As during the breaking process, a TRV builds up at the transformer terminals.
5. When the TRV exceeds the dielectric withstand of the gap, an arc ignites
6. The process continues until the contacts mate

Breaking of inductive currents in 3-phase networks
Virtual chopping

- Load breaking: 400 kW
- Current: 20 A
- Voltage peak: 97 kV
- \( \text{du/dt (breakdown)} \): 250 kV/\( \mu \)s
Virtual chopping through capacitive coupling
Exacerbates over-voltages

At re-ignition of TRV, the source-side capacitance charges the load-side cable

Re-ignition current takes return path through other phases

Return current forces current-zero of 50Hz currents in other phases >>> virtual chopping

Over-voltage probability and mitigation
Thesis Helmer, 1996 TU Brunswick

- Type A over-voltage in p.u. under different conditions (7.5 p.u. equals BIL)
- Tests on an 11kV / 1 MVA dry type transformer
- Figures in brackets give the probability of occurrence of multiple re-ignitions for an arcing time of < 0.5 ms.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Breaking of</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stationary no-load current</td>
</tr>
<tr>
<td>Without cable</td>
<td>with ZnO</td>
</tr>
<tr>
<td></td>
<td>with ZnO</td>
</tr>
<tr>
<td></td>
<td>with ZORC</td>
</tr>
<tr>
<td>80m cable</td>
<td>with ZnO</td>
</tr>
</tbody>
</table>

Surge arresters can limit the peak voltage but cannot prevent multiple re-ignitions
Mitigation means for inductive loads

- Surge arresters
  - limit the over-voltage peak values.
  - have to be adapted to the anticipated "safe" voltage levels and anticipated discharge energies.
  - but cannot avoid the fast transients, which give uneven voltage distribution on windings.
- RC - components
  - Reduce the du/dt of the recovery voltage and peak voltage.
  - Have to be adapted to the network by numerical calculations (EMTP) in order to avoid resonance oscillations.
- Filter chokes
  - Reduce the voltage rise for low current loads.
Recommended protection for medium voltage motors used with vacuum interrupters

Dr. Erik Taylor

General recommendations for motor switching


- “This paper reviews the results from an extensive EPRI project on turn insulation capability of motors and other publications in order to quantify the surge environment and the surge strength of typical utility motors…”

- “The risetimes and magnitudes of surges produced by vacuum and air-magnetic switchgear are similar…”

- “Inadequate quality control appears to be the real cause for low surge strength of poor motors…”

- “Experimental and analytical investigations indicate that modern vacuum switchgear, when used as recommended by the manufacturers, are as benign as air-magnetic switchgear for typical utility applications. In most motor applications with well designed motor supply systems, surge capacitors are not necessary; they may be required only under special circumstances…”

- “As part of the EPRI project, surges at 39 motors in 16 plants of 11 North American utilities were measured over a period of 3 years.”
Protection strategy for MV motors

1. Motor $I_{\text{stat}} < 600$ A
   - surge arrester at motor feeder
2. Surges from feeding net
   - add surge capacitor + arrester at the incoming feeder
3. Old motor, frequent starting or insulation not acc. IEC 60034-15
   - add RC circuit at motor feeder


Range of options for surge protection

From P. G. Slade, The Vacuum Interrupter: Theory, Design, and Application, New York: CRC Press, 2008, Sec. 5.3.3.
Summary

- Well established recommendations for controlling the effect of vacuum interrupter switching surges on MV motors.
- Extensive, multi-year independent study found vacuum switchgear fully compatible with MV motors.
- There are particular situations where surge protection is recommended, and these are well characterized.
- Wide range of protection options and possible locations, extensively discussed in the technical literature.
- Vacuum interrupters for motor switching is fully accepted in the market.
This paper is a reaction on

“Vacuum circuit breakers in distribution networks. Mechanical characteristics and overvoltages during switching”
By Dr. Sarin

Conclusion: In particular, use of VCB’s of certain types in medium voltage networks (especially in city distribution networks), where CLP insulation cables are used, is unreasonable due to increased insulation degradation of such cables.
Typical Mixed MV Distribution Network

- 30 MVA / HV-MV substation / cos(ϕ)=0.95
- 5 ring feeders
- Each ring 15 km cable
- Each substation 37.5 km of cable
- Each ring 15 RMU of 800kVA
- Small Industrial site: 3 per public network
- Medium size Industrial site: 1 per public network

![Diagram of Typical Mixed MV Distribution Network]

Typical Mixed MV Distribution Network 2

<table>
<thead>
<tr>
<th>Worktype</th>
<th>Type of operation</th>
<th>Number of units</th>
<th>Switching Frequency</th>
<th>Switching Voltage in [p.u.]</th>
<th>Cable Length in [km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public</td>
<td>Load</td>
<td>5</td>
<td>0.1</td>
<td>1.06 1.08 1.05</td>
<td>38 7.5</td>
</tr>
<tr>
<td></td>
<td>Earth Fault1</td>
<td></td>
<td>0.25 (e)</td>
<td>1.73 1.73</td>
<td>0</td>
</tr>
<tr>
<td>Substation</td>
<td>Load</td>
<td></td>
<td>0.2</td>
<td>1 1</td>
<td>37.5 0.02</td>
</tr>
<tr>
<td></td>
<td>Over Current</td>
<td>37</td>
<td>0.00 (e)</td>
<td>1 1.8</td>
<td>38 0.02</td>
</tr>
<tr>
<td>RMU</td>
<td>Load</td>
<td>5</td>
<td>0.03</td>
<td>1.9 0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Inrush Current</td>
<td>6</td>
<td>10</td>
<td>1 3</td>
<td>30 0.5</td>
</tr>
<tr>
<td></td>
<td>Faut</td>
<td>2</td>
<td>0.06</td>
<td>1.9 0.5</td>
<td>0</td>
</tr>
<tr>
<td>3 Small</td>
<td>Load</td>
<td>10</td>
<td>1000</td>
<td>1 1</td>
<td>30 0.1</td>
</tr>
<tr>
<td>Industrial</td>
<td>Inrush Current</td>
<td>6</td>
<td>10</td>
<td>1 3</td>
<td>30 0.5</td>
</tr>
<tr>
<td>Sites 2MVA</td>
<td>Faut</td>
<td>2</td>
<td>500</td>
<td>1 1</td>
<td>0</td>
</tr>
<tr>
<td>Medium</td>
<td>Inrush Current</td>
<td>8</td>
<td>10</td>
<td>1 3</td>
<td>0</td>
</tr>
<tr>
<td>Size</td>
<td>Faut</td>
<td>10</td>
<td>0.00 (e)</td>
<td>1.9 0</td>
<td>0</td>
</tr>
<tr>
<td>Industrial</td>
<td>10 MVA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Duration of Switching Voltage: 5 msec
Duration of Earth Fault: 1 sec ~ 1 hour
Duration of Cap. Bank: 1 minute

[Diagram of Typical Mixed MV Distribution Network 2]
XLPE Cable Ageing

**Water Treeing**
- Electro – Chemical
- Depends weakly on Electric Field
- Depends strongly on water adsorption
- Depends on frequency

**Electric Treeing**
- Depends strongly on Electric Field
- Follows CRINE’s model

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**Electrical Treeing due to Switching Surges**

![Graph showing Cable Life Time vs. Electric Field](image)

- Cable design 6/10kV, 30 Years, DIN VDE 0276-620
- Cable designed for 30y
- Graph showing Type test 4H at 4U0
- Data Boonruang Marungri

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Dr. Hans Schulekraus – 4 September 2012
Conclusions – 1

Public Distribution Network

- Switching operations don’t influence the cable life time
  - True for all CB’s; air, oil, SF6 and vacuum

- Switching surges in connected industrial sites don’t propagate into the public network and are of no concern.

⇒ (Vacuum) Circuit Breaker operations can not explain the increased failure rate in Russian cable networks
Conclusions – 2

*Industrial Network*

- All stresses due to switching surges for a given duration remain well below 10% of breakdown strength

- Surge protection on motor control centers is a sufficient precaution to respect cable life time and the cable design criterium

⇒ *Vacuum circuit breaker operations have no influence on cable life time*
⇒ *Confirms current practice in Europe, North America and China*
Panel Discussion

“Overvoltages generated by VCB at switching of inductive loads”

Dr. Alexey Chaly

Statement №1

“Deployment of VCB into electrical networks of ore factories resulted in growth of earth faults stimulated by switching overvoltages” [1]

Investigation of the only available reference [2] shown the following:
— author claims that percentage of earth faults due to switching overvoltages increased

This claim is not supported with any primary data

This claim is not supported with any methodology:
— What type of VCB was used?
— Was overvoltage protection applied?
— How different reasons of overvoltages have been discriminated?


### Percentage of failure cause

<table>
<thead>
<tr>
<th>Failure cause</th>
<th>Weight, %</th>
<th>2002—2008</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightning overvoltages</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Earth fault overvoltages</td>
<td>25</td>
<td>33</td>
</tr>
<tr>
<td>Switching overvoltages</td>
<td>10</td>
<td>38</td>
</tr>
<tr>
<td>Aging of the insulation</td>
<td>54</td>
<td>20</td>
</tr>
<tr>
<td>Mechanical stress</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Other cause</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>
Our direct inquiry to ore factories revealed the opposite situation. Chief power engineers of the factories do not notice increase of damages of insulation due to switching overvoltages after deployment VCB into their network [3, 4, 5]

1. Decree from JSC “Kuzbassenergo” from 22.10.2010
2. Response from JSC “Kuznetskiy ferroalloy”, 2012
3. Response from JSC “Iskitimcement”, 2012

Conclusion №1

Reliable field data proving that deployment of VCB into ore factories resulted in increase of insulation damages due to switching overvoltages has not been presented in the only available reference.
Statement №2

“VCB creates higher overvoltages than OCB at motor closing” [2, 6]

This was stated on the basis of experimental investigation conducted in [6] at which 3 types of VCB and 1 OCB were closed 10 times each for motor 800kW connected with approximately 100 m cable.

Experimental results

<table>
<thead>
<tr>
<th>Circuit breaker</th>
<th>Average source side phase-to-earth per unit overvoltage, p.u.</th>
<th>Average motor side phase-to-earth per unit overvoltage, p.u.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>closing</td>
<td>opening</td>
</tr>
<tr>
<td>VCB1</td>
<td>1,64</td>
<td>1,62</td>
</tr>
<tr>
<td>VCB2</td>
<td>1,54</td>
<td>1,54</td>
</tr>
<tr>
<td>VCB3</td>
<td>1,57</td>
<td>1,86</td>
</tr>
<tr>
<td>OCB</td>
<td>1,53</td>
<td>1,39</td>
</tr>
</tbody>
</table>

During investigation substantial error at measurements was committed. Voltage detection from motor side had unstable contact resulted in noise. Voltage detection from source side was OK.

Compare the oscillograms

Source side Test

Motor side Test 1

Motor side Test 2
Ratio of the maximum motor side overvoltages to the source side overvoltages

What is average overvoltage for this oscillogram?

Then why average is so important for insulation?

For insulation we would expect maximum overvoltage to be more important.
If we lined up maximum (maximum maximoro) overvoltages recorded for each CB at these ten closing operations, we would get the following:

<table>
<thead>
<tr>
<th>Circuit breaker</th>
<th>Maximum overvoltage on the source side, kV</th>
<th>Maximum overvoltage on the motor side (all oscillograms), kV</th>
<th>Maximum overvoltage on the motor side (noise-free oscillograms), kV</th>
</tr>
</thead>
<tbody>
<tr>
<td>VCB1</td>
<td>10,6</td>
<td>17</td>
<td>12,3</td>
</tr>
<tr>
<td>VCB2</td>
<td>9,2</td>
<td>13,3</td>
<td>13,3</td>
</tr>
<tr>
<td>VCB3</td>
<td>13,3</td>
<td>21,2</td>
<td>NA</td>
</tr>
<tr>
<td>OCB</td>
<td>10,0</td>
<td>19,6</td>
<td>NA</td>
</tr>
</tbody>
</table>

Conclusion №2

Experimental investigation presented in [6] has been conducted with substantial measurement and treatment errors.

At the same time it has not provided any evidence that VCB generates higher overvoltages than OCB at motor closing.

Statement №3

“To ensure safe VCB operation (from overvoltage generation standpoint) the following additional requirements shall be applied for VCB. Foreign VCB can meet all these requirements but none of the local manufacturers can meet all of them” [1]


<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-simultaneity of main contacts closing, milliseconds, not more</td>
<td>1</td>
</tr>
<tr>
<td>Non-simultaneity of main contacts opening, milliseconds, not more</td>
<td>1</td>
</tr>
<tr>
<td>Contact velocity at closing, m/s, not less</td>
<td>1,2</td>
</tr>
<tr>
<td>Contact velocity at opening, m/s, not less</td>
<td>1,5</td>
</tr>
<tr>
<td>Contact bounce duration, ms, not more</td>
<td>0</td>
</tr>
<tr>
<td>Contact resistance, micro Ohm, not more</td>
<td>40</td>
</tr>
<tr>
<td>Current chopping, A</td>
<td>3.5-5</td>
</tr>
<tr>
<td>VI pressure, Pa, not more</td>
<td>10e-4</td>
</tr>
<tr>
<td>Duration of repeatable breakdowns, microseconds, not more</td>
<td>50</td>
</tr>
<tr>
<td>VI dielectric strength at 2mm contact gap, kV/mm, not less</td>
<td>35</td>
</tr>
<tr>
<td>Breakdown voltage reduction rate at closing, kV/ms, not less</td>
<td>60</td>
</tr>
<tr>
<td>Breakdown voltage increment rate at opening, kV/ms, not less</td>
<td>75</td>
</tr>
</tbody>
</table>
Conclusion №3

Introduction of new requirements for VCB is not properly motivated.

None of the key VCB manufacturers today is prepared to claim compliance with these requirements.

Test methods for many of these requirements do not exist.

Compliance with the requirements may have opposite effect with regard to generation of switching overvoltages.
Statement №4

“Preferable CB for distribution networks are oil or SF6 circuit breakers” [7]

Conclusion №4

This statement is false as authors have not presented any proof that VCB being properly protected in accordance with the manufacturers recommendation generates more dangerous overvoltages than oil or SF6 circuit breakers.
Tavrida vision related to VCB application for motor closing

Closing of motors for any breaker results in switching overvoltages.

The most dangerous regime is associated with the closure of the first CB pole at voltage maximum followed by closure of the second and third poles in the opposite maximum of the motor natural frequency oscillation.

In this regime for ideal CB (not capable of interrupting HF currents) maximum overvoltages may reach 3.3 p.u. unipolar \(^8\) (at motor terminals) that is below requirements of IEC 60034-15 (4.9 p.u for 6kV motors) with safety margin 33%.

At the same time bipolar voltage may reach 4.9 p.u. that will result for typical motor in 3.2 (65%) p.u. interturn voltage \(^9\). This is still below insulation level prescribed in IEC 60034-15 (3.9 p.u. for 6 kV motors) with safety margin 18%.

Closing of vacuum circuit breakers is associated with the multiple restrikes that is not advantageous for insulation. From the other hand these restrikes have positive effect of limiting maximum overvoltages to lower level than for ideal breaker (<2.8 p.u. with 99% probability) \(^8\)

\(^8\) Numerical Simulation of Overvoltage Generated at Switching on Medium-voltage Motors with the aid of Different Circuit Breakers, ISDEIV Paper, 2012

\(^9\) Switching phenomena in medium voltage systems good engineering practice on the application of vacuum circuit breakers and contactors, PCIM Europe Paper RO-47, 2011
Conclusion for motor closing

We consider overvoltage effect of different CB at motor closing as approximately equal and not dangerous from IEC 60034-15 standpoint.

At the same time we cannot claim that closing of CB (of any type) is 100% safe for Russian market as GOST does not prescribe any requirements related to motor impulse withstand capability.

Tavrida vision related to VCB application for motor interruption

It seems that today there is a common vision that the most dangerous regime is interruption of starting motor that is rare or irrelevant for majority of applications.

On the other hand in this regime if VCB starts departing contacts close to natural current zero dangerous overvoltages may be generated for a wide range of motor powers and cable lengths.\(^\text{[10]}\)

This process first discovered in early 70-s and called «Voltage escalation».\(^\text{[11]}\) is relevant only for breakers having high HF interrupting performance, i.e. VCB.

\(^{[10]}\) The influence of a vacuum circuit breaker and circuit parameters of switching overvoltages generated during interruption of starting motors, ISDEIV Paper, 1996

\(^{[11]}\) Voltage escalation in the switching of the motor control circuit by the vacuum contactor, IEEE TRANS. PAS Vol. 91, 1972
Voltage escalation

Interruption of 800kW motor in the least favorable phase without overvoltage protection


To avoid possible negative effect of VCB (though having very low probability) on motor Tavrida offers application of SA in parallel to main VCB contacts. In this case voltage escalation stops at relatively early stage.

Interruption of 800kW motor in the least favorable phase with SA being installed in parallel to main VCB contacts

Maximum overvoltages does not exceed 3.0 p.u. that is less than insulations level prescribed in IEC60034-15 with safety margin 39%. 
Conclusion for motor interruption

To avoid dangerous overvoltages at interruption of starting motors we recommended installation of SA in parallel to main VCB contacts. This limits overvoltages to safe level (from IEC60034-15 standpoint).

Resulting maximum overvoltages are also lower than the ones that may be generated by ideal CB at motor closing and by transient earth faults.

Thank you