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REVIEW

Voltage transient management for Alternating Current trains with vacuum circuit breakers

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Abstract

Alternating current power supplies and rolling stock with 25 kV (50 or 60 Hz) and 15 kV (16.7 Hz) traction systems do not have the characteristics and behaviour of a typical three-phase medium-voltage distribution system. Switching inductive loads with a vacuum circuit breaker (VCB) in MV traction systems poses familiar challenges as well as some unique challenges, such as the crossing of phase change neutral sections. Transformers represent highly inductive loads due to their iron core and, thus, the consequences of energizing and disconnecting a transformer and dealing with the energy stored in its inductance must be considered within a system context. The authors of this study consider two transient phenomena associated with switching single-phase, medium voltage, AC traction transformer loads using a VCB on railway rolling stock: (i) switching transients that occur when disconnecting a transformer, particularly if lightly loaded and (ii) pre-ignition and current inrush that occurs when energizing a transformer. Both phenomena can cause reliability problems, requiring increased system maintenance or resulting in premature failures of system components. The authors review the use of controlled switching and other state-of-the-art methods to prevent or limit voltage transients when switching a transformer load by means of a VCB. The effective application of such techniques has been demonstrated in previous research or established in practical applications by manufacturers and electrical distribution network companies.

1 | INTRODUCTION

The railway traction system is unique in its composition. The railway is long and thin and the AC traction power must be distributed over significant distances. The power is delivered in single-phase sections and fed by different transformer systems, including the autotransformer, booster transformer and single transformer systems. The train is required to change between phases at regular intervals along the network.

In Continental Europe, trains often run between networks supplied with different AC voltages at one of two frequencies, i.e. 15 kV, 16.7 Hz and 25 kV, 50 Hz. This change in voltage and frequency requires the train manufacturers to have insulation coordination design for 25 kV, 50 Hz systems but have a transformer core optimised for operating at low frequencies of 16.7 Hz. Phase changes in the overhead lines (OHLE) require the train to disconnect from the OHLE and reconnect once it has passed through the neutral section separating the phases. This results in the train's transformer or transformers being regularly disconnected and energised.

Therefore, the traction system components between the pantograph and the secondary side of the transformer must be designed specifically for use on rolling stock and for the unique challenges of the railway environment. These include space constraints, vibration, frequent vacuum circuit breaker (VCB) switching and continuous running at high power levels.

Transient overvoltages can cause reliability problems, requiring increased traction system maintenance effort or resulting in electrical flashovers or premature failures of the traction system components. These failures either result in parts of a train's traction system getting isolated and the train continuing to run on reduced power or the train needing rescue by another train or locomotive. Both scenarios result in significant disruption to railway operations.

This review focusses on the traction system between the pantograph/s and the primary winding of the traction transformer/s. It also focusses on the components within this section of the traction system and their functions. The consequences of energizing and disconnecting the train's transformer or transformers routinely at neutral sections are reviewed. State-of-the-art techniques used to limit transient overvoltages on the load side of the circuit breaker (CB) due to switching of the inductive transformer load are reviewed, including the following:

- Surge arresters (SAs) [1];
- Surge capacitors [2];
- Resistor capacitor (RC) snubbers [3];
- Pre-insertion resistors (PIR) [4];
- Chokes [5]; and
- Controlled switching of the VCB [6].

Controlled VCB switching determines the VCB contact closing and contact separation times as a function of the phase angle, to prevent prearcing and current inrush when energising the transformer and to avoid transient over voltages on disconnection. Controlled switching of the VCB with transformer flux measurement can almost completely eliminate inrush currents when energizing a transformer [7, 8]. This review also considers the use of power electronic switched reactive power-type technology to limit or prevent transient over voltages when disconnecting the transformer. The objective of this review is to understand the methods for reducing both transient overvoltages due to VCB switching and transformer magnetizing inrush on AC rolling stock and the technical options that enable this.

2 | RAILWAY AC INFRASTRUCTURE TRACTION SYSTEMS

The OHLE is configured into different phase sections for convenient power delivery to the train through its pantograph interface. However, this results in the need for frequent switching on the train's traction system, due to the neutral sections required for phase separation.

2.1 | Infrastructure traction and neutral sections

'Neutral sections' in the OHLE are necessary where there is a change of phase at a feeder station, for example. When trains travel through neutral sections, the train coasts through with the traction system 'powered down' [9, 10]. However, in practice, the train's VCB is required to interrupt a small current before the train enters the neutral section, typically in the region of 3 A to 10 A.

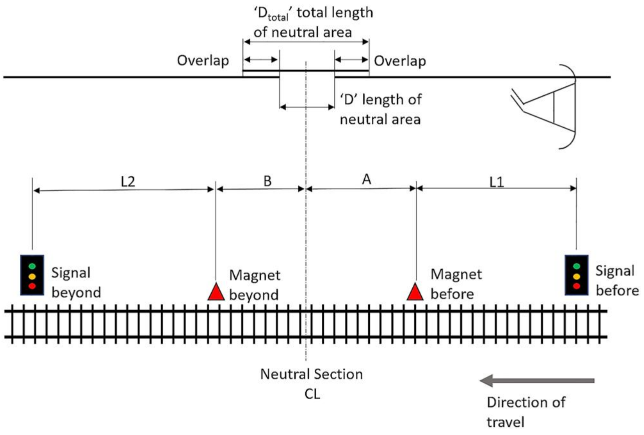

FIGURE 1 Neutral section arrangement

Figure 1 shows an example of a neutral section and the distances for the automatic power control (APC) magnets. The neutral length between phases 'D' is as short as possible, typically <10 m [11].

The distances 'A' and 'B' of the APC magnets in Figure 1 are determined by the speed and gradient of the line through the track section [12]. Depending on these factors and the length of the train configuration, the traction system will be powered down for a number of seconds as it passes through the neutral section.

With neutral sections typically spaced at 30 to 50 km intervals on 25 kV, 50 Hz high-speed rail (HSR) networks [13–15], the CB on the train opens and closes five to eight times per hour, assuming operating speeds of greater than 200 km/h [16]. Such high numbers of VCB switching operations are not typically experienced in medium-voltage (MV) electrical distribution networks.

2.2 | Rolling-stock AC traction systems—Pantograph to transformer

The operation of coupled electrical multiple units (EMU) requires careful pantograph spacing to maximise pantograph separation when the EMUs are coupled, which can therefore influence the number of pantographs required per EMU. Where multiple pantographs and transformers are installed, they are typically connected via a 25 kV bus system to allow single pantograph operation.

Figure 2 shows a generic AC traction system configuration. The main 25 kV components on the primary side of the train's transformer include the following:

Pantograph: Connects the traction system to the OHLE and is normally raised with a pneumatic cylinder. Depending on the rail infrastructure, there may be two pantographs fitted in the same roof space to cope with voltages and catenary designs that differ between infrastructures and countries.

SA1: SA or lightning arrester: normally mounted next to the pantograph and before the VCB to protect the traction system from impulse voltage spikes, such as lightning.

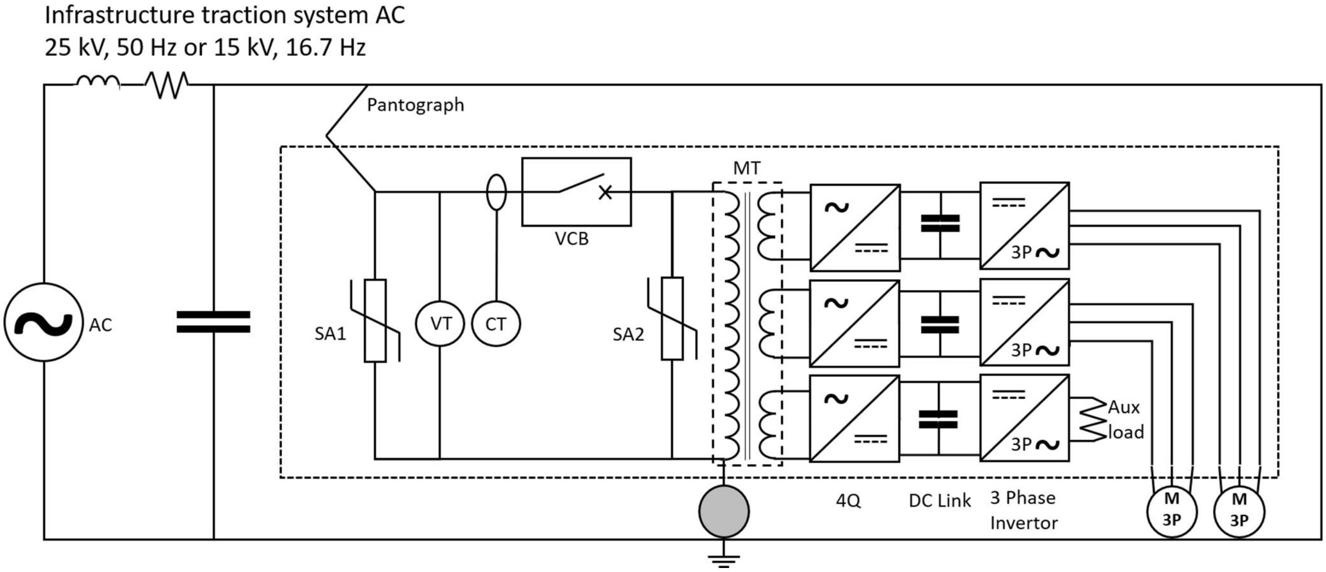

FIGURE 2 Schematic of AC traction system

VT: Voltage measurement transformer: to step down the overhead-line voltage to a measurement voltage for the train control system (TCS). An output from the VT is required for VCB controlled switching.

CT: Current Transformer: normally multiple CTs are fitted for current measurement. An output from the CT is required for VCB controlled switching.

VCB: The Vacuum Circuit Breaker is controlled by the TCS and routinely opens during neutral section breaks in the OHLE and is used for traction system protection from short circuit faults.

SA2: A medium-duty or light-duty SA is normally mounted after the VCB and before the main transformer. Its primary function is to protect the main transformer from VCB switching surges.

MT: Main transformer, the primary winding is connected at the same potential as the OHLE, number of secondary windings to suit the train configuration.

Modern AC electric rolling stock has the capability to brake using the train's traction system. The VCB will only be used to interrupt regenerative braking in case of unexpected or significant failures in the electrical systems of the train, which requires an immediate separation of the main transformer from the catenary.

3 | RESEARCH CHALLENGES OF ROLLING STOCK VCBS

In this review, the use of the latest generation of fully insulated, earth-screened and single-phase VCB intended for use on 25 kV, 50 Hz and 15 kV, 16.7 Hz systems is covered. Railway rolling stock VCB ratings are largely derived from the international standard IEC 60077-4 [17] and IEC 62271-100 [18] and other international standards cross-referred within them.

The VCB shown in Figure 3 is the latest generation of single-phase, fully insulated and earth-screened VCB intended for rolling-stock applications.

The closing and opening sequence is shown in the ABB travel time diagram [19] in Figure 4. The graph shows that galvanic contact closing is reached at time t_2, when the contact stroke has been performed. The corresponding travel S_2 is taken as the 100% value. After the initial galvanic contact, bouncing of the main contacts may take place. The contact bounce, when the initial galvanic contact is made and prior to the contact spring compression, is present in all VCBs and is a consequence of the spring and moving mass dynamics [20].

The contact spring compression when the VCB is fully closed provides most of the energy to open the VCB. In the VCB example shown in Figure 3, this is when the coil holding current is removed. Smaller springs that are also compressed on closing provide additional energy to achieve the required opening speed.

The vacuum interrupter (VI) is the single most important element of a VCB. The VI contains the electrical contacts within a vacuum, with one contact capable of moving axially. Contact separation is determined by the basic insulation level (BIL) required for the VCB. Typically, on 25 kV, 50 Hz systems this is 170 kV [21], although in some countries this increases to 185 kV.

The vacuum internal pressure is typically 10^{-4} hPa to 10^{-8} hPa [22]. The dielectric strength in the VI during contact separation is non-linear, and a significant dielectric strength is achieved with a relatively small contact separation.

The VI is a complex component and there are several challenges to overcome:

- The contacts must possess high resistance to arc erosion during both the opening and the closing operations [23];

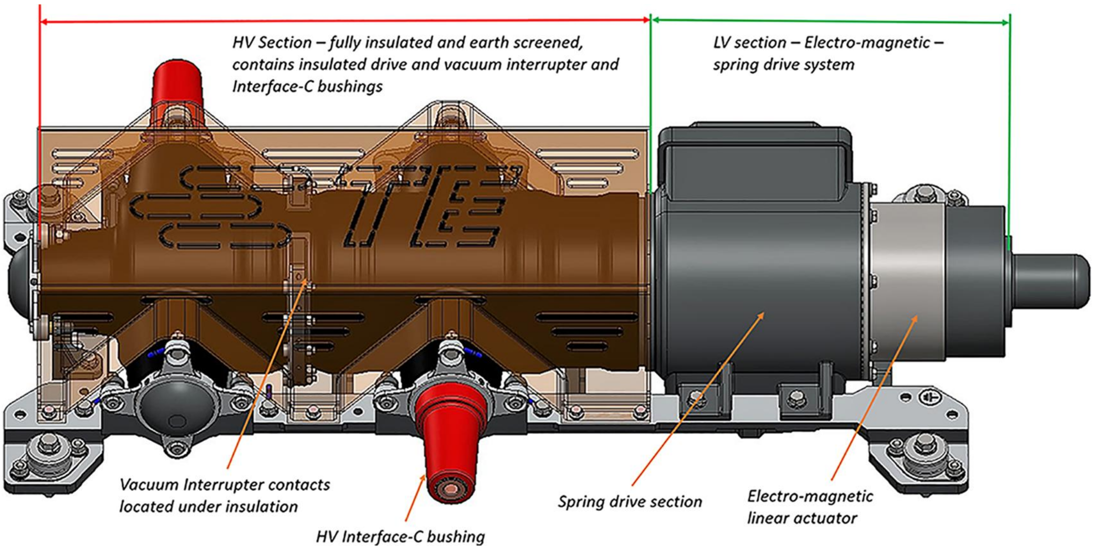

FIGURE 3 Single phase vacuum circuit breaker (VCB), source TE Connectivity

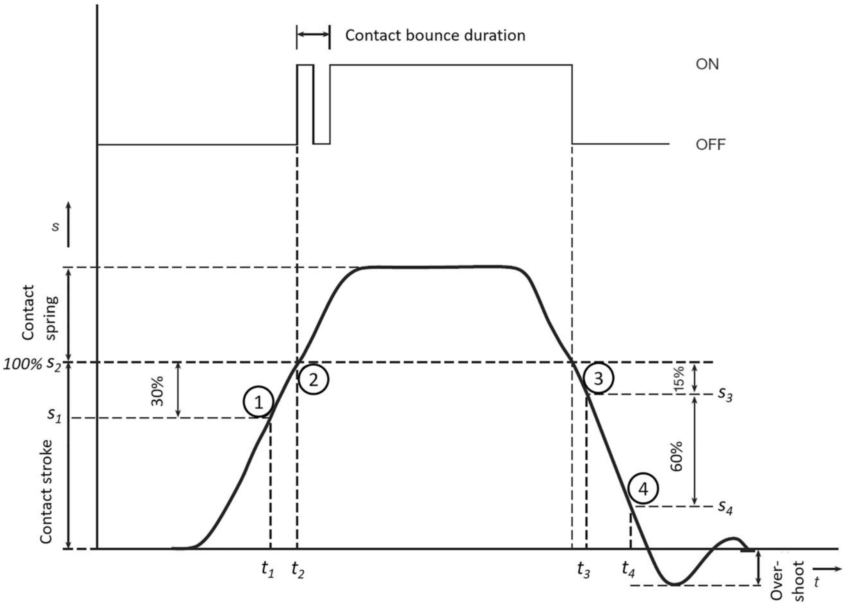

FIGURE 4 VCB close and open travel time diagram [19]

- Contact welding under short circuit conditions must be avoided, while chopping currents must be reduced to the minimum [23];
- It must interrupt short circuit currents far in excess of the standard rating, resulting in a high thermal load;
- It must be capable of switching frequently in railway rolling-stock applications ∼10 ops/hour.

The VI contact material and shape have undergone much research and refinement over the years. The contact material is a copper/chromium (Cu/Cr) alloy and the contacts are spiral shaped to generate a radial magnetic field, which has average chopping currents around 3 A and spreading between 2 A and 4 A [23, 24]. The behaviour of an arc, and consequentially, the arc voltage in a VCB VI, is different from that of high-pressure gas blast arcs found in SF_6 or air-blast-type CBs [25]. The main difference with a VCB is that the arc column is only influenced by the electrode material and the arc cessation is dominated by cathode processes [26]. The arc voltage of a low-current vacuum arc is almost entirely due to the cathode voltage drop [26]. These arc voltages typically ranging between 40 and 100 V [23].

4 | SWITCHING INDUCTIVE LOADS USING A VCB

The transformer is a highly inductive load due to the energy storage capability of its iron core.

High over voltages are observed on the load side of the VCB when switching the transformer. With an unfavourable phase angle and without the use of any protection against switching overvoltages, the dielectric strength of the system components can be exceeded, resulting in insulation breakdown and system failures.

When a CB is opened, breaking can occur at any point on the current curve. Therefore, when the VCB is opened, an electric arc is generated due to the inductive (magnetic) energy that is still accumulated in the circuit and a recovery voltage appears between the VI contacts. Therefore, switching transient overvoltages are inevitable when disconnecting a transformer, with values of 3 pu [24] not being exceptional.

In normal service conditions, as mentioned in 2.1, the rolling-stock VCB routinely switches a much lower current than the full traction load at neutral sections, typically 3 A to 10 A, referred to as 'small inductive currents' [6]. The significance of this is covered in the following sections:

5 | SOURCES OF OVERVOLTAGES

The VCB on a train is routinely required to switch a range of transformer switching scenarios, shown here from normal to worst case [27]:

1. Energizing a no-load transformer;
2. Disconnecting a no-load transformer;
3. Interruption of transformer in-rush current; and
4. Disconnecting a transformer with inductive load.

The following sources of voltage surges caused by VCB switching of inductive circuits have been identified [24, 28, 29]:

1. Current chopping;
2. Reignitions and voltage escalation;
3. VCB pre-ignitions and closing transients;
4. Travelling waves and reflections;
5. Saturation of the transformer;
6. Load characteristics that cause a current surge at the instant of switching.

Points 4, 5 and 6 are influenced by the inductance in the transformer and the length of the cable/s between the VCB and the primary transformer. The relationship of the VCB switching to the phase angle, the circuit configuration as well as the source and load characteristics will also cause different transient effects. The following sections explore these phenomena further:

5.1 | Current chopping—disconnecting transformer

The VCB have no problem in interrupting small inductive currents [6], which are typically a few Amps to some hundred Amps, normally < 600 A [30]. However, voltage transients on the load side of the VCB can occur as the instability of the arc causes current interruption before the natural zero current at short arc angles [31], leading to high di/dt [28]. Thus, magnetic energy remains in the iron core of the disconnected circuit, proportional to the chopped current [29] where the arc extinguishes, and the current is forced to a premature zero.

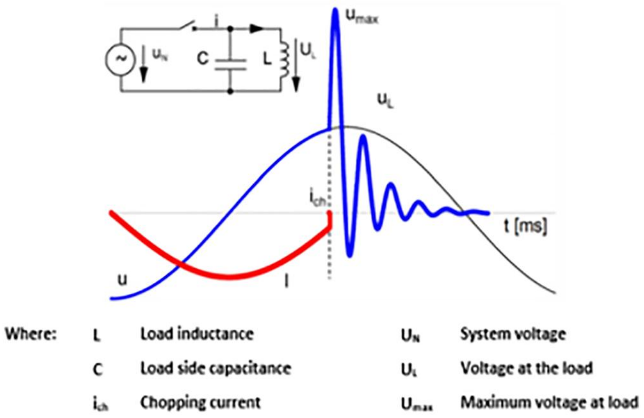

FIGURE 5 Current chopping on AC wave [29]

The energy $1/2LI^2$, which is present at the point of current chopping in the inductive load, will oscillate via the parasitic capacitances of the system. Therefore, the overvoltage amounts to approximately $U_{max} = i_{ch} \times \sqrt{L/C}$ [24], with a frequency of $f = \frac{1}{2\pi\sqrt{L/C}}$ [30]. The graph in Figure 5 [29] shows the point of current chopping (i_{ch}) before the current zero and the resultant overvoltage U_{max}.

The chopping current magnitude depends on the moment of contact separation, where the closer the contact opens to zero current, the higher the chopping current [33]. However, the severity of the current chopping phenomenon is dependent on the switching characteristics of the VCB [6] and the traction system circuit that is being interrupted [34].

In a study by J.F. Perkins [35], it has been found that overvoltages increase as the transformer MVA rating increases. This reflects the fact that the magnetizing current also increases with MVA.

5.2 | Reignitions and voltage escalation—disconnecting transformer

The reignition phenomenon can occur in all types of CBs but occurs particularly in VCBs [36]. Reignition and voltage escalation can occur in the process of disconnecting the inductive load due to a high di/dt value and conversion of magnetic energy into electric energy, when the voltage can reach high values [37]. Reignitions occur when the overvoltage across the separating VCB contacts following current interruption exceeds the dielectric strength of the opening gap [38]. After the current is interrupted, the energy stored in the inductive load oscillates between the inductive load and the capacitance [6, 30] and a variety of oscillating currents then start to flow through the VCB [6].

Because the cable and CB inductance are small, the frequency of this oscillating current can be quite high, typically 100 to 200 kHz [39].

Multiple reignitions can occur as the voltage increases with each reignition. This phenomenon is known as voltage escalation [29, 38]. With increasing voltage, caused by each reignition, the corresponding high-frequency transient current rises [29]. Figure 6 [32] shows the first reignition, which is cleared. But the overvoltage exceeds the dielectric strength of the opening gap and there is a second reignition. This reignition produces a high-frequency transient as the two sides of the separating contact gap are electrically brought back together [39].

This repetition of reignitions and high-frequency current interruptions can occur several times, as both the increasing amount of energy in the effective load inductance and the increasing contact spacing permit each successive reignition to occur at a higher mean voltage [35].

Current chopping and any subsequent reignitions are important phenomena, as the high-frequency overvoltages can lead to damage to the transformer and the insulation of the traction system [39].

5.3 | Pre-arcing—energizing transformer

When closing the contacts of a VCB, pre-ignition or pre-strike is unavoidable [24]. As the VCB contact gap reduces, the dielectric strength decreases from its maximum value to zero [40]. Dielectric breakdown happens prior to the contacts' touching and a current flows through the plasma, resulting in the occurrence of a steep voltage surge [3, 24, 40].

The pre-striking phenomenon when energizing a transformer is similar to the reignitions when disconnecting a transformer [35]. However, because the contacts close and the contact gap decreases, no voltage escalation is possible [24] and the arc clears at the transient zero crossing prior to closing.

As a result of a load-side oscillation, the overvoltage on the terminals of an inductive load can easily reach 3 pu [24]. These pre-strike surge voltages are significant due to their amplitude and their rate of rise [41].

5.4 | Travelling switching waves and reflections—energizing transformer

When a circuit that is connected by cables is energised, the voltage in the entire circuit does not instantaneously assume the value of the source and the voltage applied at one end of the cable travels to the other end rapidly close to the speed of light [3]. Therefore, travelling waves can be observed in the cable(s) when energizing an inductive load.

The connecting cables on rolling stock are short, in the region of tens of meters (typically between 7 m to 25 m). For these short cables, the capacitance is small: the surge impedance of a cable may be under 50 Ω [42], whereas the surge impedance of the transformer is higher, anywhere

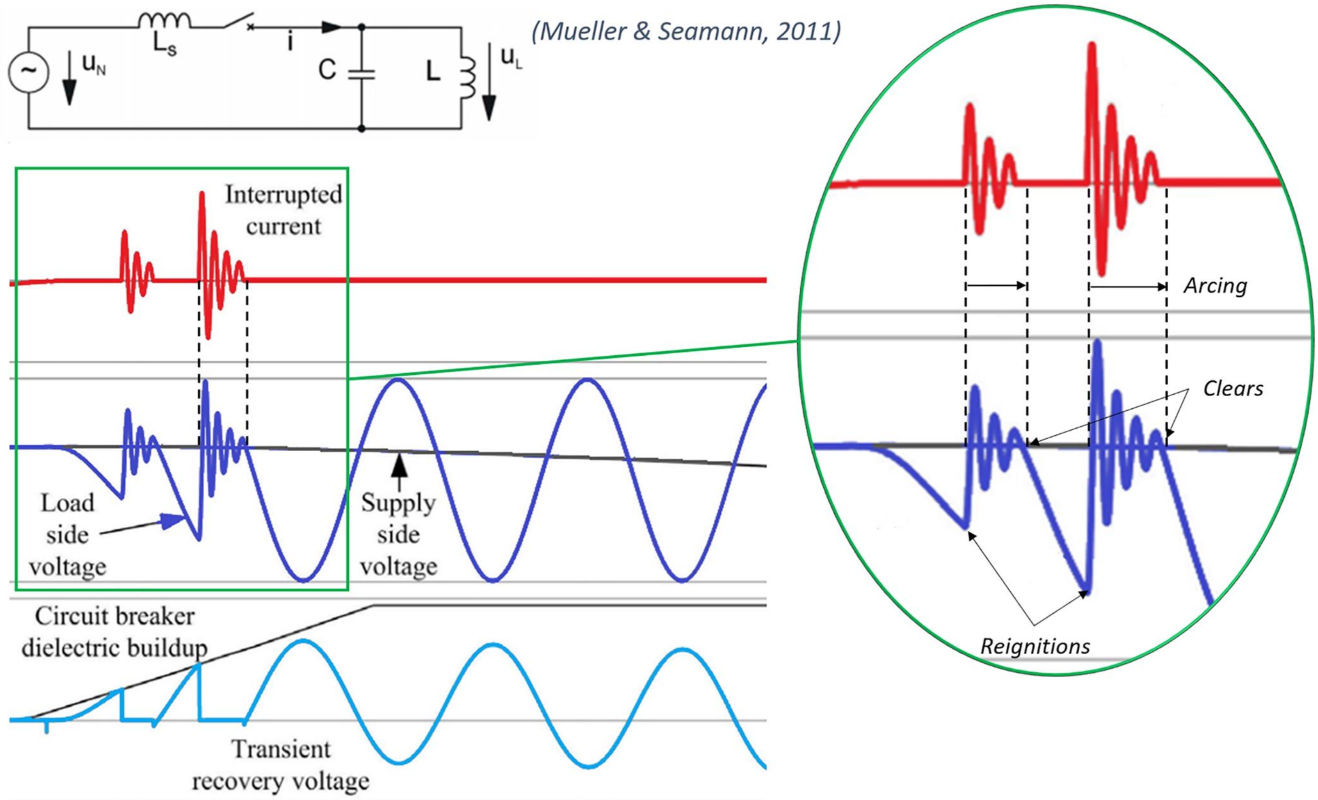
(Mueller & Seamann, 2011)

FIGURE 6 Reignitions during inductive load switching [32] between 300 and 3000 Ω [42]. Therefore, a travelling wave is produced when the cable is energised, if prestrikes occur in the CB, or if reignitions occur in the VCB on disconnection. The wave is reflected when it meets a discontinuity in surge impedance between the cable and the transformer [42]. This can result in a high transient frequency at the transformer terminals [3, 42] and the reflection can be as high as two per unit [42].

6 | OVER-VOLTAGE PROTECTION

There have been several research approaches to limiting overvoltages due to VCB switching of inductive loads [29]:

- SAs to limit the magnitude of surges;
- Surge capacitors to attenuate the surge rate of rise;
- RC circuits to dampen high frequency transients and prevent repetitive impacts.

When a surge capacitor is used in combination with the SA, the rise of the transient overvoltage is slower and the peak voltage is limited. Therefore, the number of SA activations is greatly reduced [42].

In recent years, train manufacturers have been fitting ferrite cores on the load side of the VCB, presumably to influence any switching overvoltage rise time. The benefits and effectiveness of this approach will be covered in the following sections:

6.1 | Over-voltage surge protection using SAs

The use of SAs in rolling stock traction systems has become common practice to reduce overvoltage due to uncertainty of circuit parameters of traction systems. SAs, originally introduced to protect against lightning induced overvoltages [42], can also be used for protection against VCB-induced transients [1].

Lindell and Liljestrand [43] have studied the effectiveness of different types of over-voltage protection devices using the same MV system and VCB when disconnecting an inductive load. They found that when an SA is installed on the load side of the CB, phase to ground, it also limits the transient recovery voltage. The benefit of this is that when the SA starts limiting the overvoltage, reignitions in the VCB stop.

To understand the relationship between the VCB switching and the SA function, both the scenarios, energizing a transformer and disconnecting a transformer, should be considered [1]:

A. Limitation of transient overvoltages due to prestrikes and reignitions when the CB is closed. A 'high current' passes through the SA;
B. Limitation of transient recovery voltage when the CB is open. A 'low current' passes through the SA.

Overvoltages can occur when the VCB is opened; the return path for this current is through the capacitance on the load side of the VCB. Installing an SA on the load side of the VCB will open an alternative path for the current, which will be shared between the capacitance on the load side of the CB and the SA [1]. Therefore, the key is to provide a return path for the current in the transformer winding. So there is no interruption, even when the CB is open [1].

A disadvantage of MOA SAs, typically used on rolling stock, is that they are a self-sacrificing component [44], which degrades over time, determined by the magnitude and duration of the impulses. This is a limiting factor for an SA, as there is also no simple and reliable method to determine the condition of an in-service SA when installed in a circuit.

6.2 | Over-voltage surge protection using surge capacitors

Surge capacitors on the load side of the VCB protect the load from steep rates of rise in the recovery voltage [23]. When a surge capacitor is used in combination with the SA, the rate of rise of the transient overvoltage slows down and limits the peak voltage [42], greatly reducing the number of SA interventions.

Dullini, Lindell and Liljestrand [2] considered the addition of a surge capacitor between the CB and the transformer to limit the current chopping level when disconnecting small inductive loads. They found that by adding a surge capacitor between the transformer terminals and the ground, the transient overvoltage during switching decreased by a factor of 6. The additional load-side surge capacitor influences the chopping current by acting as a source, sustaining periods of momentary current reduction after an arc instability and allowing the excitation of a subsequent arc instability during this period [2]. However, the optimisation of the capacitance or use of a variable capacitor as well as the methods of closed-loop switching control of the capacitor with the VCB are not covered in this research.

6.3 | Over-voltage surge protection using resistor capacitor snubber circuits

Resistor-capacitor (RC) snubbers are not typically used on rolling stock with 25 and 15 kV traction systems. However, the use of RC snubbers is recommended for frequently switched transformers that are lightly loaded or unloaded as it is the most likely condition to overstress the transformer [3].

Adding a resistor to the surge capacitor and SA provides damping, which reduces the dc offset of the transient overvoltage waveform [42] and reduces the dv/dt of the recovery voltage and peak voltage [45] and therefore reduces the probability of reignitions within the VCB [3].

The RC snubber provides an alternative return path for the magnetically stored energy in the load side inductance at the opening of the CB [43], but they have the following downsides:

- RC Snubbers can inject high amounts of reactive power into the network due to their high capacitance [46].
- The resistive part of the circuit continuously consumes electric energy, even in normal operation [47].

6.4 | Over-voltage surge protection using zinc oxide RC surge suppressor circuit

The zinc oxide RC (ZORC) surge suppressor consists of a capacitor, a resistor and a zinc oxide surge suppressor [48] and could be potentially used on rolling stock traction systems. Should a steep front switching overvoltage larger than 1.0–1.5 pu occur, the ZORC device will activate and reduce the equivalent resistance in series with the capacitor [49].

With a ZORC, the reflections of steep wave fronts are minimized, and high-frequency restrike current zeros in the switch are eliminated [50]. In a model of switching overvoltages on a ship service transformer, it is said that it is possible to reduce overvoltages to more moderate and acceptable levels, at approximately 2.0 pu [28].

As with SAs, ZORCs absorb energy during switching events to attenuate the oscillations, but this has a subsequent ageing effect on the device. As the ZORC also has an RC absorption circuit, it also consumes electric energy across the resistor during normal operation.

6.5 | Transient inductors/chokes/ferrites

Ferrite rings or 'chokes' are used in gas-insulated switchgear (GIS) to suppress very fast transients during switching of sulphur hexafluoride gas CBs. By putting ferrite rings around GIS CB conductors, it is possible to change their wave impedance and affect the travelling waves propagating between the CB and the load [5].

The magnetic ferrite material is used to dampen the energy of the transient over-voltage surge. The transient over-voltage energy is temporarily converted to magnetic energy within the ferrite. A ferrite material has different frequency response characteristics, magnetic conductivity, loss and saturation. These characteristics influence the equivalent parameters of the ferrite rings and can cause the magnetic material used for ferrite rings to go into saturation [51]. Once the ferrite ring goes into saturation, its equivalent inductance reduces to nearly zero. The amount of saturation depends on the ferrite material used. By layering the ferrite material it is possible to modify the magnetic field strength and consequently the saturation characteristics [51]. Simulation modelling and experimentation are useful tools for optimising ferrites.

As the ferrite material absorbs energy when attenuating the oscillations, this degrades the ferrite material over time. The degradation is determined by the magnitude and duration of the impulses, same as a SA.

The use of a transient inductor on the output of the VCB installed on rolling-stock has become more prevalent in recent years, this is presumably to reduce voltage steepness and number of re-ignitions generated during switching of low load transformer.

6.6 | Circuit breaker—PIRs

In transmission and offshore windfarm applications, closing or PIRs are sometimes added to the CB [52, 53]. Long transmission cables are energised in these applications and, often, shunt reactors are also installed [53]. CB PIRs are also sometimes used in AC transmission systems when energizing unloaded power transformers [4, 54, 55].

The PIRs are installed as part of the CB and are intended to dampen transients and limit the magnetic inrush during energizing [53]. During a close operation, the resistor is inserted at a predetermined time before the main contacts of the CB close [6]. The function of the resistor is to limit the peak value of the inrush current [55] and to accelerate the current damping to zero [4]. Once the CB contacts are fully closed, the PIR switch is opened as it must not be present during an open operation of the CB [6].

Figure 7 shows the PIR installed in parallel with the CB (Figure 7a) and in series with the CB (Figure 7b) [53]. The selection of either of these configurations depends on the CB design and the electrical stress imposed by the system being switched [53].

Since overvoltages depend on the timing of the CB contacts closing, controlled switching is increasingly being used instead of PIRs [6, 52]. This avoids the mechanical complexity of the PIR and its switch, which lead to reduced system reliability and require additional maintenance, making this technology less attractive for use on rolling stock where the CB is switched frequently, contrasting with arrangements in MV installations.

7 | OVER-VOLTAGE PROTECTION USING CONTROLLED VCB SWITCHING

With additional electronic control equipment, it is possible to switch the VCB at a pre-determined point on either the voltage or the current AC wave. It is possible to control the VCB during both closing and opening. Controlled switching is an

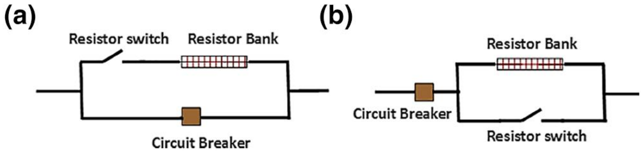

FIGURE 7 Pre insertion resistor configuration: (a) parallel (b) series [53]

established method for avoiding switching transients in MV applications [56].

The challenge for controlled switching is to issue control commands so that the VCB contacts start moving and are able to reach the required electrical and mechanical targets at the optimal moment [57]. VCBs are mechanical machines which come with small differences in the operating parameters due to mechanical tolerances. The switching speeds of VCBs can also be affected by environmental conditions, such as ambient temperature and mechanical wear over the lifetime of the VCB.

The latest generation of rolling-stock VCB with power electronic actuation drives, however, show much more consistent switching performance in comparison to their pneumatically actuated predecessors. Typically, the required repeatability and accuracy of contact separation at a specific point on the waveform is often ±1 ms [58].

Figure 8 shows an example implementation of controlled switching using a single-phase VCB for a rolling-stock application. On a standard installation, the TCS would issue a command to 'close' or 'open' directly to the VCB control unit and the VCB would switch randomly, relative to the phase angle. Figure 8 shows the voltage and current measurement on the source side of the VCB. For 'controlled switching', an output from these measurement devices is connected to a point-on-wave (POW) monitor. The TCS issues the 'close' or 'open' command to the POW controller, which then initiates the VCB's response by controlling the instant of contact separation with respect to the voltage or current wave form, depending on whether the VCB has been commanded to 'close' or 'open'. Following the command to close or open the VCB, it is necessary to insert an intentional synchronising delay, determined by the VCB's mechanical closing and opening times and the actual phase angle of the target making or breaking instant, which can be a number of half cycles in duration [6].

7.1 | Over-voltage surge protection using controlled VCB switching on disconnection

A technique used to limit the overvoltage at disconnection is controlled VCB opening, where the VCB contacts open with respect to the phase angle of the current. Controlling the point of contact separation determines the arcing time. Therefore, if the contact separation is just after a current zero, crossing the contact gap separation should be sufficient to ensure interruption without reignitions [6].

The controlled switching of the CB is an appropriate method to reduce the opportunity for reignitions [6]. But in practice, controlled open switching to prevent/reduce switching transients is more effective when applied in combination with other protection measures. Therefore, when controlled opening is applied,

- Arcing time can be minimized and
- When combined with other measures, such as RC snubbers or SAs, the surge protection can limit the amplitude of any subsequent overvoltage.

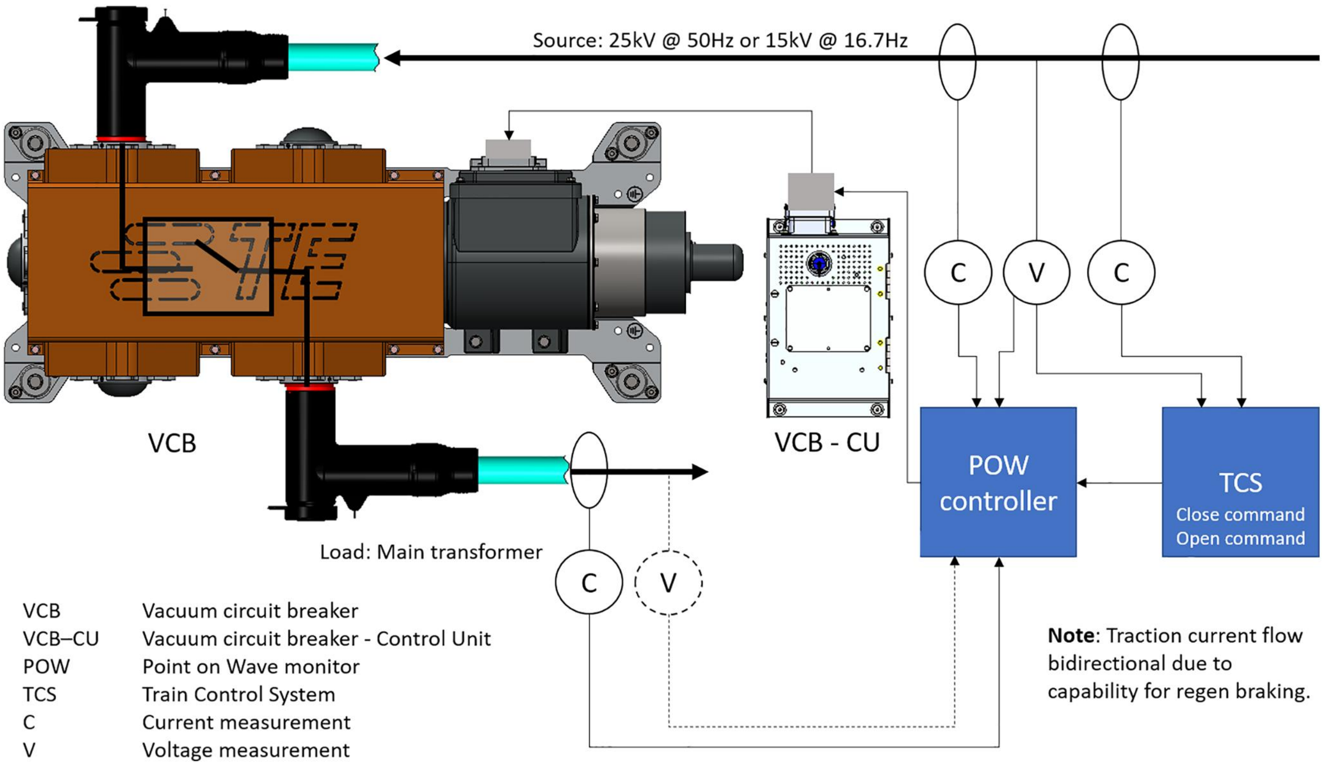

FIGURE 8 Principle of controlled switching—single phase vacuum circuit breaker

7.2 | Controlling the energizing switch on angle

By closing the CB at the voltage supply crest instant, it is possible to limit the magnetizing inrush current on the off-load traction transformer [59]. This method has become a widely accepted means of reducing magnetizing inrush in high-voltage and MV power systems [8]. However, without the transformer core flux measurement, current inrush and transient overvoltages can still be significant [60].

In order to eliminate inrush current, the remaining residual transformer core flux that results from the previous disconnection must be considered. When a sinusoidal voltage $u(t) = U_o \cos(\omega t)$ is applied on the primary winding of the transformer at instant t_0, a flux $\phi(t)$ is established in the magnetic core of the transformer and can be calculated as follows [40]:

$$\phi(t) = \phi_r + \frac{1}{N}\int_{t_0}^{t} u(\tau)d\tau = \phi_r - \phi_o \sin(\omega t_0) + \phi_o \sin(\omega t) \qquad (2)$$

The optimal instant to energise a transformer is when the 'prospective' flux is equal to the residual flux. [Figure 40, 61, 62] refer to 9 [40].

This is equivalent to selecting the switching instant t_0 is $\phi_r - \phi_o \sin(\omega t_0)$ in accordance with the flux and voltage formula [40]. The point of optimal energisation in Figure 9 [40] is shown following the voltage peak [61]. However, the point of commanding the VCB to close will need to be earlier to allow for the closing of the drive system and an allowance for timing variances will need to be factored in.

To enable the measurement of the transformer residual flux, an additional measurement voltage transformer is required on the primary side or secondary side of the transformer [8]. Refer to Figure 8.

The residual flux is derived by measuring and integrating the voltage prior to and during steady state de-energization of the transformer, which therefore allows the residual flux (final value of the integrated voltage) to be derived [63]. The following closing operation is then controlled so that the inrush current is minimized by optimizing the time instant of making the contact, in relation to the supply voltage [6]. The application of controlled switching onboard rolling stock has not been widely applied, although several train manufacturers have previously made trials using pneumatically actuated VCB [64].

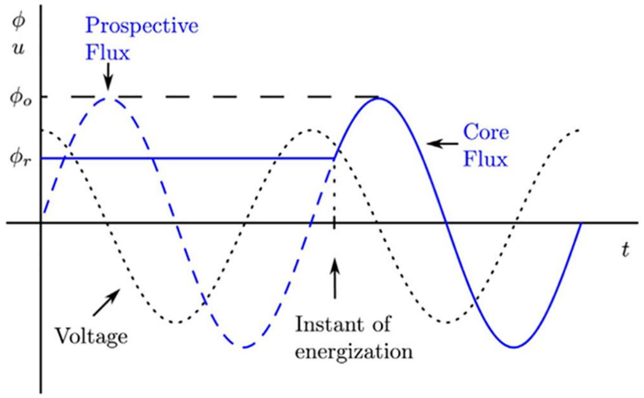

FIGURE 9 Optimal energization of single-phase transformer [40]

8 | POWER ELECTRONICS TECHNIQUES FOR FURTHER CONSIDERATION—FACTS

Flexible AC Transmission Systems (FACTS) were originally developed for high-voltage transmission networks (typically > 100 kV). FACTS are solely built with power electronics to increase transmission capacity, improve the stability and dynamic behaviour of the electrical transmission system and ensure better power quality [65]. Aspects of FACTS are now applied to MV distribution networks to improve power quality [66].

Many FACTS for MV networks are based on thyristors, which enable fast control of transients with a response time of less than one cycle on average [67].

Xu, Chen, et al. have proposed a super capacitor powered electronic system, which is used to mitigate overvoltages across the traction system electrical equipment due to arcing caused by intermittent OHLE pantograph disconnection. Overvoltages occur at the pantograph when the arcing current is cut off [47]. The bidirectional converter and a supercapacitor system are used to absorb the inductive energy from arcing at the pantograph interface. The circuit configuration in Figure 10 [47] shows the additional converters, the supercapacitor and the pantograph interface arcing as Q_{arc}. The supercapacitor system could also be used to countenance voltage fluctuation of the traction power supply [47], similar to a static var compensator in FACTS.

The possible benefits for reducing the transient overvoltages from VCB switching are not considered by Xu, Chen, et al. However, their research supports the hypothesis that a thyristor switched capacitor (TSC) could be an effective measure to prevent the current chopping phenomenon. However, the opportunity for applying this technology in conjunction with closed-loop control of the VCB switching to improve the traction system performance, particularly during the switching of the VCB, requires further research.

9 | COMPARATIVE ANALYSIS

Much research has been conducted into the methods of transient surge suppression. All the techniques covered are used in electrical distribution systems and their strengths and weaknesses are well understood. The application of the different types of technology is dependent on system behaviour, space availability and reliability. To achieve the best

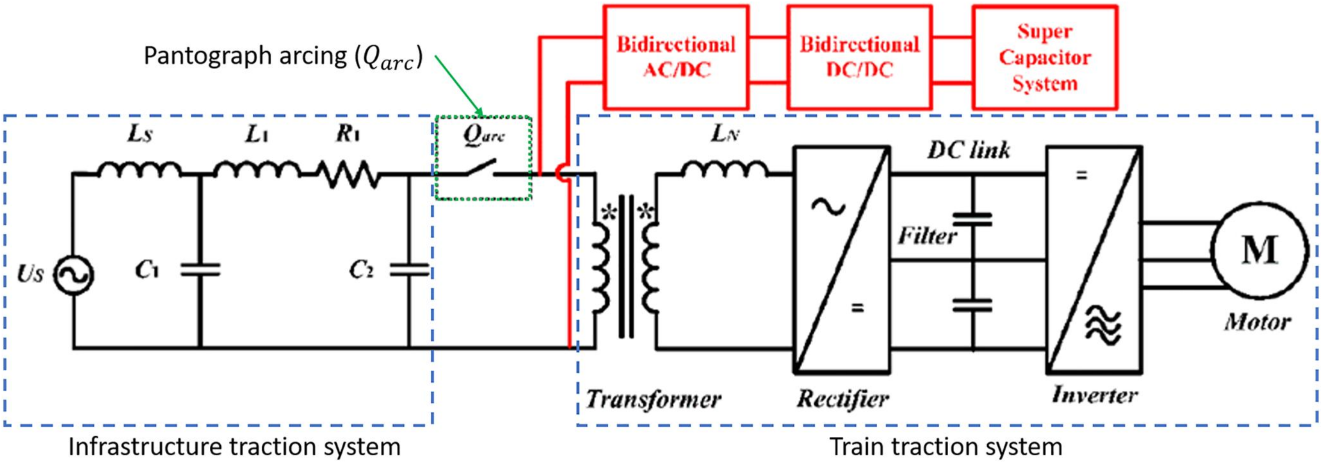

FIGURE 10 Bidirectional converters and super capacitor circuit configuration [47]

TABLE 1 Strengths & weakness comparison

Item	Strengths	Weakness
Surge arrester (SA)	Low resistance during surges, so that over-voltages are limited. Reduced risk of equipment failures. Low cost component in comparison to other options.	SAs do not limit the rate of rise of the transient overvoltages. SAs degrade over time, determined by the magnitude and duration of the impulse and there is no reliable test to measure their health.
Surge capacitor	Surge capacitor protects the transformer from steep rates of rise in recovery voltage. The number of SA operations is greatly reduced because of the slower rate of rise.	Best implemented with a SA to optimise system performance.
Resistor capacitor (RC) snubber	Reduction of probability of reignitions. Reduced risk of equipment failures	Reactive power in the network could cause a reduction of the power factor due to their high capacitance [46]. The RC absorption circuit will consume electric power across the resistor even in normal operation [47]. Combined size of resistor and capacitor can be relatively large compared to existing traction system components.
Zinc oxide RC (ZORC)	Reduction of probability of reignitions. Reduced risk of equipment failures. Low resistance during surges, so that overvoltages are limited.	The RC absorption circuit consumes electric energy across the resistor even in normal operation. Physical size of ZORC is relatively large.
Ferrite/choke	Ferrite rings or 'chokes' can be used in switchgear to supress very fast transients during CB switching. Low cost component in comparison to other options.	As the ferrite material absorbs energy when attenuating the oscillations, this will degrade the ferrite material over time.
Pre-insertion resistors	Limit the magnetic inrush of the transformer. Following magnetizing inrush, the resistor can be switched off. Reduction of transients during energizing.	Can only be used on closing of CB and energizing transformer (in the context of an inductive system). Increase in number of components and a switch reduces system reliability and increases maintenance.
Vacuum circuit breaker (VCB) controlled switching	Reduction of probability of reignitions on disconnection. Reduction of inrush current. Improvement of power quality. Reduced risk of equipment failures. Enhanced performance of the VCB. Realtime measurement of VCB switching. Better maintenance planning.	Increased system complexity, which could affect system reliability. Switching accuracy of VCB. Environmental conditions affecting VCB switching behaviour. Best implemented with transformer flux measurement to optimise system performance.
Thyristor switched capacitor (TSC)	Effectively used in SVCs to compensate for dips in the system voltage.	Using TSC in a rolling-stock application is an untested method. Potentially expensive solution compared to passive components.

possible outcome, a combination of the approaches reviewed is almost certainly required. Table 1 explores the strengths and weaknesses of the state-of-the-art and power electronic TSC technology.

All of the protection methods shown in Table 1 are used in electrical transmission and distribution systems, and some on rolling stock. All have their strengths and weaknesses, as stated in the table. The authors would struggle to rank them from best to worst, as this is driven by the system configuration, component parameters and the particular requirements of the application. The authors plan to address the question of how much overvoltage or damping is achieved by the different approaches in a future study.

10 | TECHNIQUE APPLICATION

Lacroix, Taillefer, et al. [55] studied the use of PIRs in comparison with controlled switching of a CB when energizing a distribution transformer. They found that the best inrush current mitigation technique was to use an independent pole-operated CB and a controlled switching technique with measurement of the residual flux in the switched transformer [55]. By using the controlled switching technique, it was possible to eliminate the inrush current [55]. When using the PIR technique with random CB switching, the inrush current was relatively high 50% of the time [55]. Presumably, the two techniques were not tried together, as the controlled switching technique is highly effective on its own.

Controlled CB opening may be used to prepare for the next closing operation, as interruption at a natural current zero leads to the lowest residual flux [6].

A research study by Liljestrand and Lindell [1] has shown how effective SA can be in mitigating switching transients on disconnection. It has also been shown in a research study by Dullini, Lindell, and Liljestrand [2] that, with the addition of a surge capacitor, it was possible to reduce switching overvoltages significantly as well as reduce the number of SA operations.

11 | CONCLUSION

The switching transient overvoltage prevention measures reviewed in this study have been successfully applied in MV distribution systems and other MV applications for many years. This raises the question as to why the measures reviewed have not routinely been used in rolling-stock traction systems. In many instances, some of the measures have been adopted, e.g. the use of SAs is now common practice on rolling-stock traction systems for both protection from lightning and vacuum circuit-breaker switching transients. The SA effectively limits the peak of the transient voltage.

However, SAs do not limit the rate of rise of the transient overvoltage. By using a surge capacitor in combination with a SA, the rate of rise of the transient overvoltage can be slowed down and the peak voltage can be limited. However, the use of surge capacitors is rarely seen in rolling-stock traction systems between the VCB and the primary transformer.

The use of ferrites in rolling-stock traction systems connected to the vacuum circuit-breaker output are now applied more routinely. The magnetic ferrite material is used to dampen the energy of the transient over-voltage surge by temporarily converting it into magnetic energy within the ferrite. Tuning of the ferrite ring or rings is required to avoid saturation. The use of ferrite rings could be a cheap and easy-to-apply method to dampen transient overvoltages from both vacuum circuit-breaker switching and arcing at the pantograph interface and is worth further research to understand the scope of what can be achieved.

The use of resistor–capacitor snubbers and surge capacitors is rarely seen in rolling-stock traction systems, presumably due to their size, cost and the space they consume versus the reliability benefit they bring.

Controlled switching techniques when energizing and disconnecting a train's transformer are also not widely used, despite the benefits of doing so in MV distribution and other MV applications. With modern rolling-stock VCBs having electro-magnetic drive systems and highly repetitive switching accuracy, the use of controlled switching with residual flux measurement of the transformer core could bring benefits in reducing or eliminating magnetizing inrush, when reenergizing the frequently switched transformer.

The use of power electronics in transmission and distribution electrical networks in the form of FACTs has proved to be very effective in preventing voltage dips and harmonic distortion [66] in the network. It would be worthwhile to carry out further research into using power electronic thyristor switched-capacitor technology on rolling stock to introduce reactive power when disconnecting a small inductive load. Further analysis is required to understand the potential of this technology. With the ability to provide reactive power in combination with the controlled switching of the VCB, it could be used to reduce transient overvoltages and any subsequent reignitions on disconnection of the transformer/s when switching a small load, as routinely performed on trains at neutral sections.

The authors will address in a future study on simulation, the question of the extent to which overvoltages or damping can be optimised with the techniques reviewed in this study, particularly the use of controlled VCB switching, SA, ferrite rings and TSC in an AC rolling-stock setting.

CONFLICT OF INTEREST

The authors have no conflict of interest to disclose.

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