Resonant overvoltage challenges during pre-magnetization energization of power transformers

J. Kolb, M. Hatlo, T. Nestli

Abstract **- The energization of large power transformers can give rise to substantial inrush currents that result in significant voltage variations and create operational challenges in the system. Various mitigation methods are used in the industry to prevent transformer saturation and the associated inrush phenomena. Pre-magnetization (pre-mag) is based on the energization of the power transformer from the secondary side, using an auxiliary supply system in the network. Inadequate system design of the pre-mag system can introduce low-order resonances in the supply circuit during the energization sequence. These resonances may be excited during energization, posing the risk for significant overvoltages in the system and thermal overloading of the pre-mag transformer. This paper addresses resonant challenges associated with pre-mag energization of power transformers based on experience with various real-world projects.**

Keywords**: Transformer, inrush current, energization, pre-magnetization, resonant overvoltages.**

I. Introduction

The energization of power transformers represents normal operational events in industrial power systems and can give rise to inrush currents and associated voltage variations [1,2]. Transformer energization is usually associated with temporary voltage drops during the event. Depending on power quality and operational requirements, different voltage variations are considered to be acceptable during the event.

Various mitigation methods have been developed and are available in the industry. For high voltage power transformer energization, controlled point on wave (PoW) switching is the most common method to mitigate transformer saturation and associated inrush currents. Pre-insertion resistors are also used, however, require additional high voltage circuit breakers. Pre-magnetization (pre-mag) energization [3] is an alternative if an auxiliary supply source is available on the secondary side of the power transformer. The method is often employed in remote offshore installations but has also been utilized in onshore power systems.

The pre-mag energization principle is illustrated in Figure 1. Here, the power transformer is energized from the secondary (low voltage) side, before the circuit breaker (CB3) on the primary (high voltage) side is closed. The pre-mag system is usually supplied from a low voltage auxiliary system (typically 400 V or 690 V) and includes the pre-mag transformer and pre-insertion resistor (PIR), in addition to supply cables, switching devices and other auxiliary equipment for the operation.

The pre-mag energization sequence is typically based on the following steps:

1. Simultaneous energization of the pre-mag transformer and power transformer by closing circuit breaker CB1.
2. Bypassing the pre-insertion resistor by closing CB2.
3. Closing the high voltage circuit breaker CB3
4. Open CB1 to the pre-mag system

The different switching events are delayed with a sequential manner that depends on system requirements.

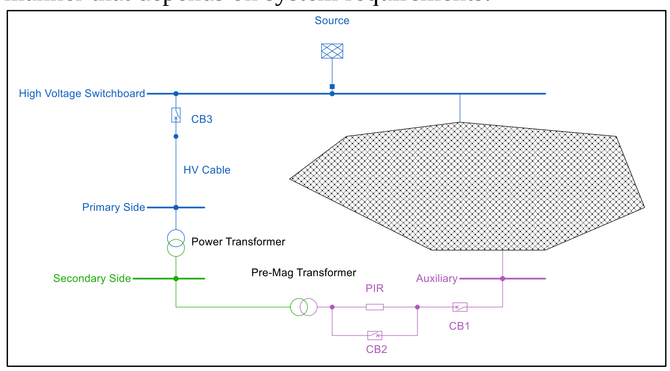

Fig. 1: Pre-magnetization (pre-mag) energization principle

In general, the pre-mag energization is a simple and robust alternative to controlled PoW switching or use of pre-insertion resistors on the high voltage side. However, the authors have been involved in various projects, where pre-mag energization resulted in sever overvoltages in the system or a thermal overloading of the pre-mag transformer during the energization sequence. The problem was usually observed in systems where the primary side operation voltage exceeded 100 kV in combination with primary side feeder cables exceeding 100 m length. The primary side high voltage feeder cable can introduce temporary low order resonances in the supply system, if the pre-mag transformer is improperly designed. Resonant excitation during transformer energization is studied detailed in [4]. The authors have experienced in various projects that the resonant phenomena was not addressed during the design phase. Instead, designs were based solely on steady state considerations, leading to systems with resonance issues that were typically identified only during commissioning.

This paper addresses the resonant challenges associated with pre-mag energization systems. The investigation is based on a detailed simulation model, representative for industrial power systems. The steady state design criteria which is typically used in the industry for pre-mag system are presented and discussed.

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Frequency domain and EMT time domain simulations are then carried out to evaluate the pre-mag energization for the network in Figure 2 with different high voltage feeder cable lengths. Based on the analysis, systems with resonant challenges are identified and presented. Furthermore, mitigation measures to prevent resonant challenges associated with pre-mag energization are provided and discussed. PowerFactory is used for frequency domain and EMT time domain simulations.

II. Power System Model

Pre-mag energization is investigated in this paper for the 110/11 kV 75 MVA transformer in the industrial network shown in Fig. 2. The model is based on a real-world system, however, was generalised in order to account for confidentiality with the client. The network is supplied from the 220 kV transmission system though two 220/110 kV 250 MVA transformers. The power is distributed to the industrial facility by a 110 kV gas insulated switchgear (GIS) which functions as the main hub for the system. The GIS station supplies electricity to a range of loads, including three large 30 MW load commutated inverter (LCI) drives, which are directly connected to the 110 kV level via dedicated step-down transformers. In addition, various distributed loads are supplied at the 22 kV and 400 V level through corresponding step-down transformers. The short circuit level at 400 V is 10-12 MVA (15-17 kA).

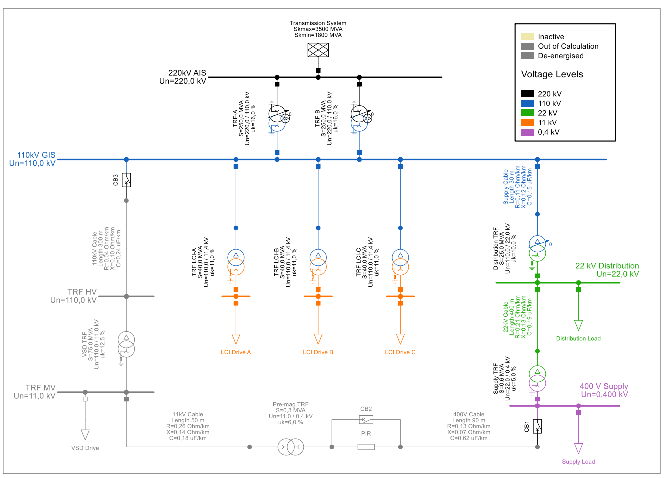

Fig. 2. Network model of industrial power system

The industrial facility includes a 110/11 kV 75 MVA transformer which provides power to a dedicated 60 MW load at the 11 kV level. The transformer is connected to the 110 kV GIS with a high voltage feeder cable. Due to the complexities and limitations of implementing controlled PoW switching or high voltage pre-insertion resistors within the existing 110 kV GIS infrastructure, pre-mag energization with supply from the local 400 V system was chosen as alternative in the project. The length of the feeder cable at the transformer primary side is usually below 50 m, but can be longer. Therefore, different feeder cable lengths of 10 m, 50 m, 100 m, 200 m and 300 m are considered in this work.

Frequency domain and EMT time domain analysis of the pre-mag system require accurate models of the 75 MVA power transformer, the 110 kV high voltage feeder cable and the pre-mag system (pre-mag transformer and pre-insertion resistor). The corresponding models are essential for the accurate simulation and assessment of the phenomena. The presentation of the supply system from 220 kV to 400 V is also important, however, not discussed in detail in this paper. Most essential parameters such as MVA ratings and positive sequence impedances are provided in Figure 2. Surge arresters are not considered in the analysis.

A. Power Transformer 110/11 kV 75 MVA

The parameters for the 110/11 kV 75 MVA power transformer are documented in Table I. The magnetization impedance with its non-linear saturation characteristic is placed in the starpoint (middle) of the transformer. The linear part of the saturation curve is derived from the no load current, and the final slope of the magnetization inductance is defined by the air core reactance. A polynomial function is used and fitted to the linear and saturated inductance of the magnetizing branch. Stray capacitances are included, however not relevant, as they are significantly lower than the feeder cable capacitance.

TABLE I
Power transformer parameters

Parameter	Value	Unit
Primary voltage (HV)	110.0	kV
Primary voltage (LV)	11.8	kV
Rated power	75	MVA
Vector group	Dyn11	-
Short circuit impedance uk	14.0	%
Copper losses	225	kW
No load current	0.1	%
No load losses	30	kW
Knee flux	120	%
Saturation exponent	33	p.u.
Air core reactance	0.28	p.u.

B. 110 kV Power Cable 3x1x800 mm2 Al

The 75 MVA transformer is connected to the 110 kV GIS with a 3x1x800 mm^2 Al feeder cable. The cable system is rated with U_m=123 kV and the cable screens are earthed at both sides. The cable model is based on a geometrical modelling input, using the actual geometry of the single core cable and laying arrangement (trefoil in air). The positive and zero sequence parameters of the cable system are documented in Table II. For the EMT time domain simulations, the cable is represented using a frequency-dependent distributed phase-domain model (ULM) which is available in PowerFactory. Cable lengths of 10 m, 50 m, 100 m, 200 m and 300 m are considered and will result in different pre-mag system designs.

TABLE II
110 kV feeder cable parameters for 50 Hz

Parameter	Positive sequence	Zero sequence	Unit
Resistance	0.044	0.431	Ω/km
Inductance	0.309	0.435	mH/km
Capacitance	0.240	0.240	µF/km
Conductance	0.076	0.076	µS/km

C. Pre-Magnetization (Pre-mag) System

The design of the pre-mag system is typically based on steady state considerations only and rated based on the reactive power generated by the power transformer and high voltage feeder cable during no load conditions.

The pre-mag transformer power rating $S_{r,PM}$ is here sized from the fundamental frequency steady state power flow $S_{PM,fl}$, which is calculated from the high voltage feeder cable current / charging power Q_{cable}, the reactive power flow of the magnetizing impedance of the 75 MVA transformer Q_{TRF} and the no load losses of the corresponding transformer $P_{0,TRF}$ according to the Equation (1). The charging power Q_{cable} of the cable is calculated based on the nominal voltage of the transformer primary side (110 kV), the system frequency f (50 Hz), the cable capacitance C'_{cable} (0.24 µF/km) and the high voltage feeder cable length l_{cable} according to Equation (2). The 75 MVA transformer reactive power demand and no-load losses can be derived from Table I and are 68.7 kVAr and 30 kW respectively. The power rating $S_{r,PM}$ is selected to be higher than the power flow $S_{PM,fl}$ to provide some margins and prevent overloading of the pre-mag transformer. Table III documents the pre-mag transformer ratings for the system in Figure 2 with different high voltage feeder cable lengths.

The winding ratio of the pre-mag transformer is selected to match the pre-mag system supply voltage (400 V) and the secondary side voltage of the 75 MVA transformer (11.8 kV). The short circuit impedance is generally designed with u_k=4%. The X/R ratio is assumed to be 4. Table II documents the parameters of the pre-mag transformer used for the simulation model. Pre-mag transformers are typically designed with linear magnetizing inductance, causing only a slight increase in magnetizing current as flux rises. As a result, their saturation curve is of minor significance and can be modelled as linear. Furthermore, the impact of the relatively small pre-mag transformer (<1 MVA) on energization transients is minimal compared to that of the much larger power transformer.

$$S_{PM,fl} = \sqrt{\left(Q_{HV,Cable} - Q_{TRF,main}\right)^2 + {P_{0,TRF,main}}^2} \quad (1)$$

$$Q_{HV,Cable} = {U_n}^2 \cdot 2 \cdot \pi \cdot f \cdot C'_{cable} \cdot l_{cable} \quad (2)$$

$$R_{PIR} = \sqrt{3} \cdot \frac{{U_n}^2}{S_{PM,fl}} \quad (3)$$

The magnitude of the pre-insertion resistor (PIR) is designed to limit the steady state voltage and initial inrush current prior to bypassing the resistor. Based on project experience, the resistor is typically designed to limit the voltage on pre-mag transformer side to 50% of the nominal voltage. The required resistance can be calculated from Equation (3). Different high voltage feeder cables results in different PIR magnitudes which are document in Table III. The energy capability of PIR resistors is typically several hundred kilo joules (kJ).

The pre-mag energization transients are investigated with the different feeder cable lengths and associated pre-mag transformers from Table III, using the network model in Fig. 2 and modelling input parameters from above.

TABLE II
PRE-MAG TRANSFORMER PARAMETERS

Parameter	Value	Unit
Primary voltage (HV)	11.80	kV
Primary voltage (LV)	0.40	kV
Rated power	see below 1.)	kVA
Vector group	Yy11	-
Short circuit impedance	5.0	%
X/R ratio (copper losses)	4	-
No load current	0.2	%
No load losses	0.30	kW

1.) The rated power depends on the feeder cable length and is different for the various cases discussed in this paper. Corresponding values are document in Table III.

TABLE III
PRE-MAG TRANSFORMER KVA RATING AND PIR MAGNITUE

Feeder cable length	Power flow $S_{PM,fl}$	Pre-mag transformer rating	PIR magnitude
10 m	67 kVA	100 kVA	4.2 Ω
50 m	38 kVA	50 kVA	7.3 Ω
100 m	38 kVA	50 kVA	7.4 Ω
200 m	118 kVA	170 kVA	2.4 Ω
300 m	207 kVA	250 kVA	1.3 Ω

III. FREQUENCY DOMAIN NETWORK

Several projects in the past have shown that resonant challenges arise, if pre-mag systems are solely designed based steady state considerations, as outlined in section II-C. Prior to closing of circuit breaker CB3 in Fig. 2, the high voltage feeder cable and the pre-mag transformer form a parallel resonant circuit. The resonance frequency is calculated according to Equation (4) and mainly influenced by the high voltage feeder cable capacitance C_{Cab} and pre-mag transformer leakage inductance L_σ. Depending on the feeder cable length and pre-mag transformer design, low order resonances may be introduced temporarily during the energization sequence.

The built-in PowerFactory network impedance frequency sweep calculation is used to analyse the network model in Fig. 2 in the frequency domain. For the frequency domain analysis, the circuit breakers CB1 and CB2 are closed, resulting in the operating conditions which are apply during the pre-mag energization, once the PIR is bypassed.

$$f_0 = \frac{1}{2\pi} \cdot \frac{1}{\sqrt{L_\sigma \cdot C_{Cab}}} \quad (4)$$

$$L_\sigma = \frac{u_k}{100\%} \cdot \frac{{U_n}^2}{S_{r,PM}} \cdot \frac{1}{2 \cdot \pi \cdot f} \quad (5)$$

Fig. 3 shows the network impedance for the different network configurations with different high voltage feeder cables from 10 m to 300 m and associated pre-mag transformer ratings. Power transformers connected with short high voltage feeder cables to the GIS do not exhibit temporary low order resonances during the energization. However, systems with longer feeder cables show low order resonances between 2nd and 4th order harmonic that can be excited from inrush currents during the pre-mag energization. It is important to note that the resonances are not directly related to the high cable length but a result of the steady state design criteria for pre-mag systems which is typically used in the industry. This design criteria seems to introduce a parallel resonance in pre-mag systems with longer high voltage feeder cables.

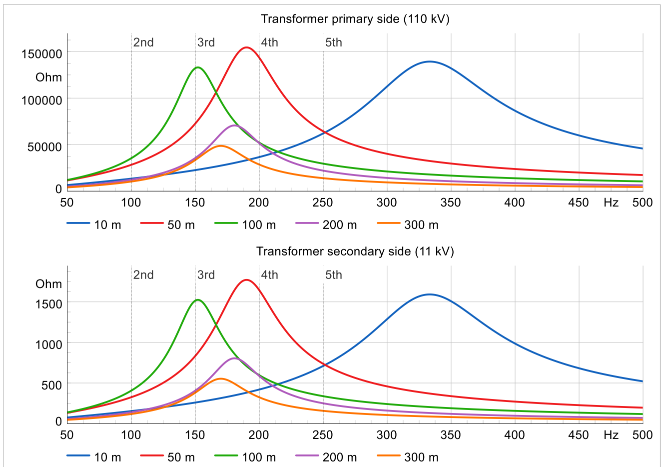

Fig. 3. Network impedance 110 kV side of main transformer during pre-mag energization (once PIR is bypassed and before CB3 is closed)

IV. EMT Time domain analysis

The pre-mag energization is investigated in detail in this section, using EMT time domain simulations. PowerFactory is used as simulation tool. PSCAD has also been used for similar projects and benchmarking purposes earlier.

A. Simulation Sequence and Method

The energization simulations are carried out for the network model in Fig. 2 and applying five different feeder cable lengths with the corresponding pre-mag transformer and pre-insertion resistor ratings from Table III. The sequence of events are:

- t = -0.1 s: start of simulation in steady state
- t = 0.0 s: close CB1 (energization with PIR)
- t = 0.2 s: close CB2 (bypass PIR)
- t = 0.5 s: close CB3 (close HV circuit breaker)

The time delays between the different events are in reality longer. The delay between CB1 and CB2 is typically a few hundred milliseconds and the delay between CB2 and CB3 can rage from a few seconds to minutes or hours. However, this is not relevant for the analysis in this paper. Multirun simulations are considered for the closing event of CB2 (bypassing pre-insertion resistor). The pre-mag energization is investigated for two different operation conditions, considering different operating voltage of 100% and 105% for the pre-mag supply system. Higher voltages are associated with full load conditions and lower voltages with no load conditions, respectively. The residual flux in the power transformer is of minor importance since the initial energization occurs through the pre-insertion resistor. The pre-insertion resistor reduces the initial voltage significantly (approximately 50%) and provides substantial damping to the circuit. As a result, saturation levels in the power transformer remain below the knee point, even when considering high levels of residual flux. The paper includes sensitivities with different pre-mag transformer ratings and modified PIR resistances to show the impact of alternative designs with regard to the design criteria in section II-C.

B. Pre-mag Energization 100% Supply Voltage

The pre-mag energization transients are shown in Fig. 4 and Fig. 5 for the system with a 10 m high voltage feeder cable, showing the RMS supply voltage, phase-to-phase voltage at the transformer primary side, 400 V circuit breaker currents (CB1) and absorbed energy in the PIR. Fig. 6 and Fig. 7 show the corresponding results for a system with a 100 m feeder cable.

The transients during the initial phase of the pre-mag energization, with the pre-insertion being active in the circuit, are negligible. The inrush currents are very low and voltage variations in the supply system and overvoltages are not observed. The pre-insertion resistor mitigates saturation of the 75 MVA transformer and associated inrush phenomena successfully. During the second phase of the energization sequence, when the pre-insertion resistor is bypassed, significant transients arise. Transformer saturation is triggered by a phase jump in the supply voltage that arises when the pre-insertion resistor is bypassed. The voltage phase jump drives the 75 MVA transformer into saturation for both cases with a 10 m and 100 m cable.

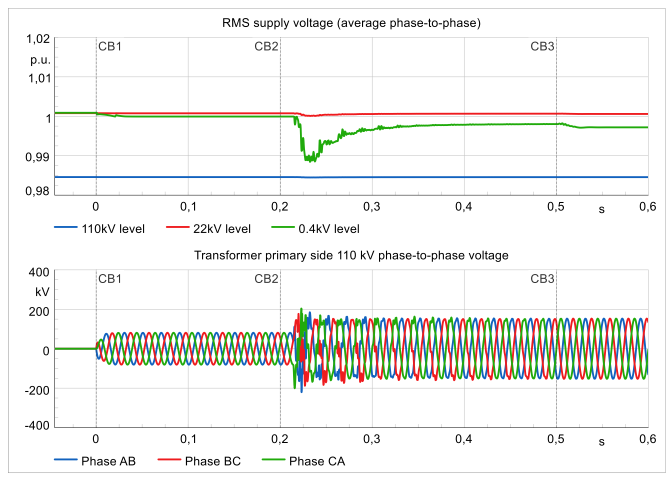

Fig. 4. Voltages for case with 10 m feeder cable

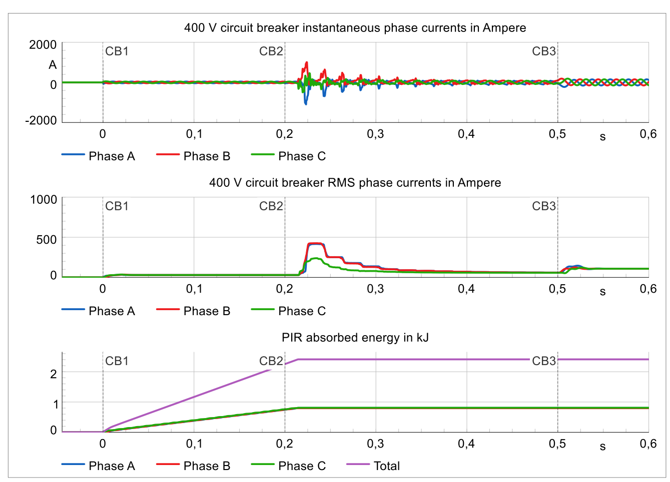

Fig. 5. Currents and absorbed PIR energy for case with 10 m feeder cable

The inrush currents at the 400 V level reach approximately 1200 A_{peak} / 450 A_{RMS} and 1700 A_{peak} / 690 A_{RMS} for the 10 m and 100 m cable case respectively and contain significant second and third order harmonics. The magnitude of the inrush currents is low compared to the short circuit level (15-17 kA_{RMS}). The system with the 100 m cable has a parallel resonance close to 150 Hz (3rd order harmonic) which is excited during the event and results in significant transient switching overvoltages, which are not observed for the other case with a 10 m cable. The absorbed energy in the PIR remains well below its energy capability. The voltage variations in the supply system are negligible during the complete sequence. The pre-mag system mitigates successfully voltage variations in the supply system, which are typically associated with the energization of large power transformers.

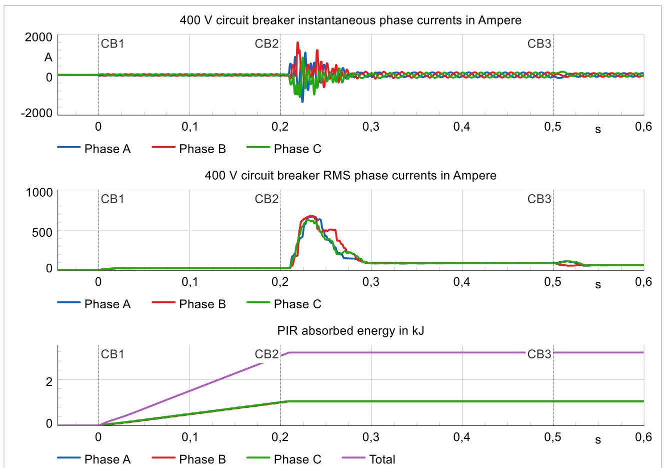

Fig. 6. Voltages for case with 100 m feeder cable

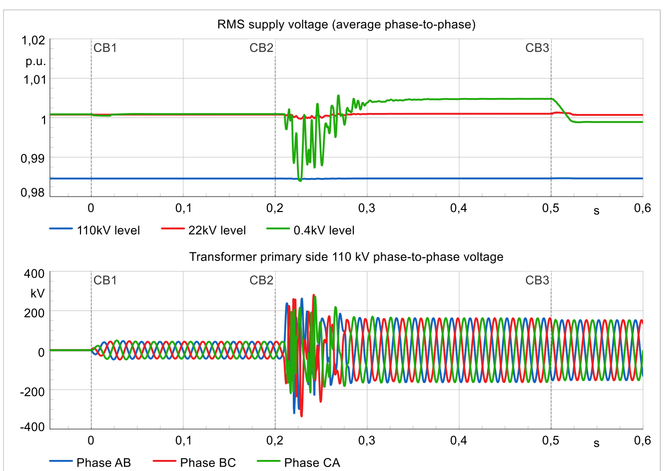

Fig. 7. Currents and absorbed PIR energy for case with 100 m feeder cable

The transient inrush currents and associated overvoltages depend on the transformer saturation level which depends on the introduced phase jump. The phase jump depends on the time instance for bypassing the PIR resistor. Uncontrolled switching is used for the 400 V circuit breaker and thus, the bypassing angle is of random nature. Multirun simulations are therefore required for the analysis, taking into consideration all relevant pre-resistor bypass angles for one period (20 ms).

Fig. 8 shows the maximum overvoltages at the 110 kV level of the main transformer arising during the pre-mag energization for all systems designs with cables from 10 m to 300 m and for pre-insertion bypass angles from 0° to 360° in 1° steps. Cumulative distribution functions (CDF) are derived for the cases and presented in the same plot. Highest overvoltages occur for the system with a 100 m high voltage feeder cable. High overvoltages are also observed for the system with a 200 m and 300 m feeder cable. The corresponding systems have low order resonances with frequencies that match with the harmonic currents contained in the inrush currents. The corresponding resonances are being excited during the pre-mag energization and are the root cause for the overvoltages.

Furthermore, the RMS steady state current exceed the rating of the selected pre-mag transformer for some systems (e.g. 100 m high voltage feeder cable). If the closing event of the 110 kV circuit breaker CB3 is delayed for a longer time, the thermal overloading of the pre-mag transformer can become a problem and has been observed in projects in the past.

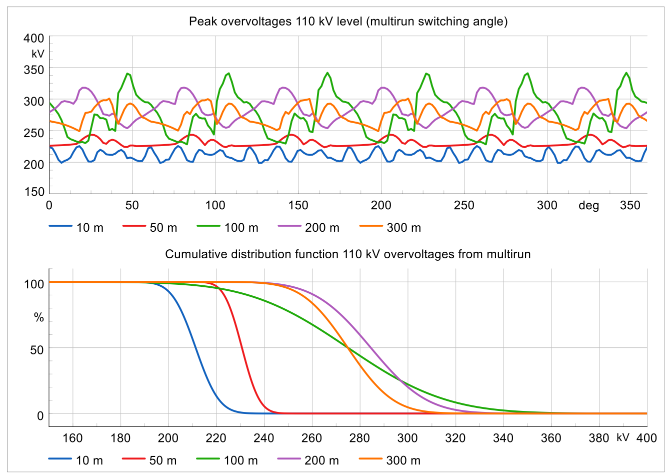

Fig. 8. Multirun simulations with different PIR bypassing angles for one power frequency period (360° / 20 ms) for systems with different high voltage feeder cable length and CDF function of corresponding overvoltage events

C. *Pre-mag Energization 105% Supply Voltage*

The operation voltage of the supply system to the per-mag transformer is usually not regulated directly and depends on the load level. Based on the winding ratios in typical industrial systems, nominal voltage is usually obtained at full load condition, while increased voltages occur at no-load conditions. Depending on the distribution transformer winding ratios, the no-load voltages range typically between 105% and 110%.

The multirun simulations for the system in Fig. 2 with different cable lengths are repeated in this section, assuming 105% as operation voltage in the 400 V supply system, reflecting no-load conditions for the network. Fig. 9 shows the maximum peak overvoltages at the primary side (110 kV) of the 75 MVA transformer for different cable length and as function of the pre-insertion bypass angle. Increased operating voltages result in increased transformer saturation and associated inrush currents, exciting resonant overvoltages. The maximum peak overvoltage from all multirun simulations for the case with the 100 m high voltage feeder cable increases from 342 kV_{peak} to 361 kV_{peak}, while the average maximum peak overvoltages increases from 275 kV_{peak} to 307 kV_{peak}, corresponding to an average increase of nearly 12%. The peak current in the 400 V circuit breaker which supplies the pre-mag system increases from 1677 A_{peak} to 1849 A_{peak} .

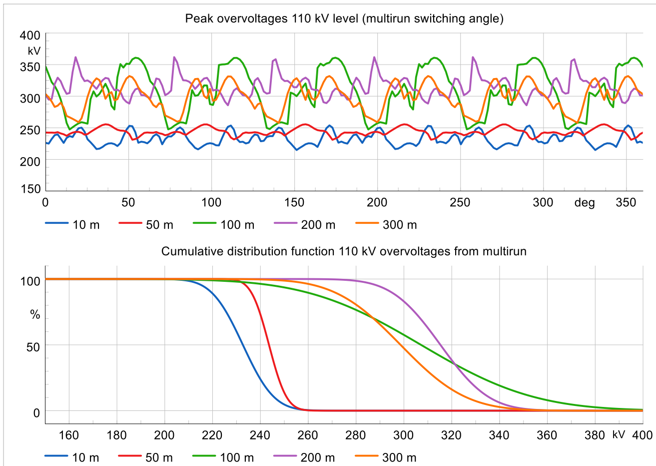

Fig. 9. Multirun simulations with different PIR bypassing angles for one power frequency period (360° / 20 ms) for systems with different high voltage feeder cable length and CDF function of corresponding overvoltage events

D. Pre-Mag Energization After Design Improvement

The previous sections have shown that transformer energization based on pre-mag systems can introduce resonant challenges in the system. Problems can arise if the pre-mag system design is based solely on steady-state considerations (see section II-C) and fails to account for resonance conditions caused by a suboptimal combination of high-voltage feeder cable length and pre-mag transformer rating. These resonant issues can be prevented by the following options:

- Alternative design of the pre-mag transformer (kVA rating) that mitigates low order resonances.
- Modified pre-insertion resistor magnitudes, reducing the phase jump during PIR bypassing.
- Operational measures, e.g. reduced supply voltage.

The primary aim of improved pre-mag system designs is the mitigation of low order resonances with frequencies that match the harmonic content of the main transformer energization inrush current. This can be achieved by moving the parallel resonance to higher frequencies which can be realized by reducing the capacitance or inductance in the circuit (see Equation (4)). The capacitance is dominated by the high voltage cable and can usually not be changed, as the cable length and parameters are given by the site requirements. The inductance is dominated by the pre-mag transformer. The corresponding inductance can be reduced by increasing the pre-mag transformer kVA rating. The effect of the pre-mag transformer rating (assuming that transformer impedance remains constant at uk=4%) is shown in Fig. 10 for the case with a 100 m high voltage cable, using frequency domain analysis. Increasing the pre-mag transformer rating moves the resonances effectively to higher frequencies. The multirun simulations from section II-A were repeated for the 100 m cable case, using different pre-mag transformer kVA ratings. The simulations show that the overvoltages are significantly reduced with changed pre-mag transformers. Fig. 11 shows the maximum peak overvoltages for multirun simulations with pre-mag transformers rated from 50 kVA (base case according to steady state considerations in section II) to 500 kVA. The maximum peak overvoltages are significantly reduced for pre-mag transformers with 100 kVA or higher. This confirms the results from the frequency domain analysis. Moving the parallel resonance limits resonant overvoltages during the energization significantly.

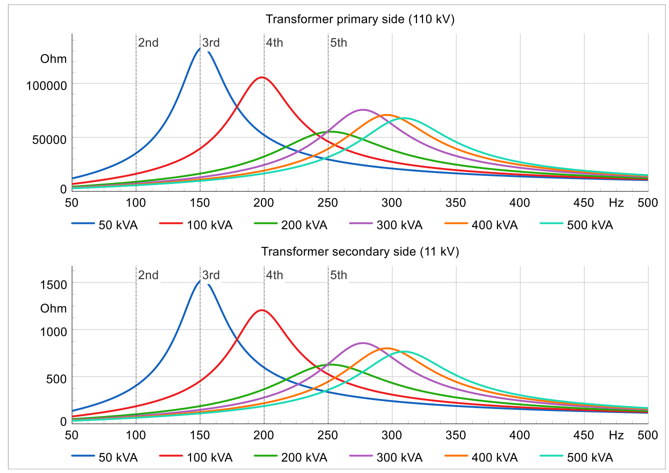

Fig. 10. Network impedance 110 kV side of main transformer during pre-mag energization (once PIR is bypassed and before CB3 is closed) with increased pre-mag transformer ratings

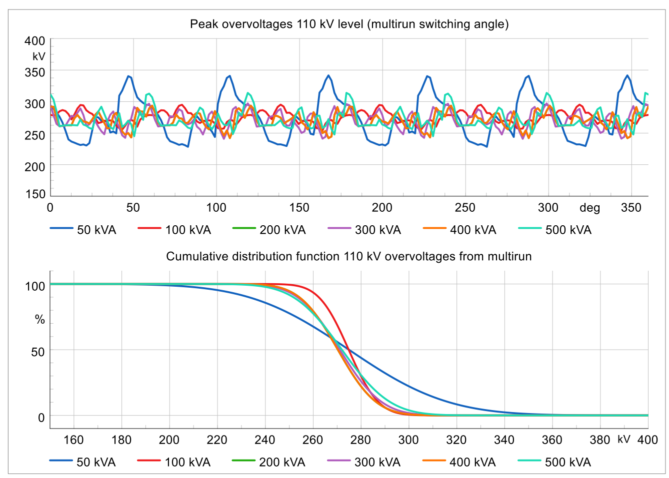

Fig. 11. Multirun simulations with different PIR bypassing angles for one power frequency period (360° / 20 ms) for system 100 m high voltage feeder cable and different pre-mag transformer kVA ratings and CDF function of corresponding overvoltage events

The authors have been confronted with resonance issues for pre-mag energization systems several times during the commissioning phase of a project. Here, the system was already installed and ready for energization. Redesigning the pre-mag transformer was not a viable option. However, it was discovered that adjusting the pre-insertion resistor could also reduce overvoltages by minimizing the phase jump during PIR bypassing. Changing the resistor of the pre-mag system is usually simpler and faster and requires only minimal modifications of the pre-mag system design (only the pre-insertion resistor needs to be changed). The modification of the resistor does not remove the low order resonance in the system but limits the excitation of the corresponding resonance during the energization sequence by reducing the inrush current.

Fig. 12 shows the maximum peak overvoltages from multirun simulations for the case with a 100 m high voltage feeder cable, assuming different pre-insertion resistor magnitudes. According to steady state considerations described in section II, the resistor was originally selected with 7.4 Ω. Reducing the resistor to 2.0 Ω or less, reduces the resonant overvoltages during the energization sequence significantly.

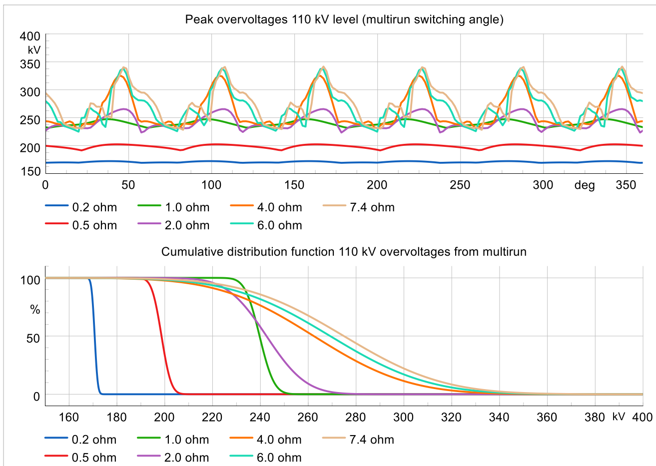

Fig. 12. Multirun simulations with different PIR bypassing angles for one power frequency period (360° / 20 ms) for system 100 m high voltage feeder cable and different pre-insertion resistors

V. DISCUSSION

Inadequate system design of pre-mag systems can introduce low-order resonances in the supply network during the energization sequence. The resonances may be excited from inrush currents during the energization, posing the risk for significant overvoltages in the system and thermal overloading of the pre-mag transformer. The resonance is formed mainly by the high voltage feeder cable and leakage inductance of the pre-mag transformer. Bypassing the pre-insertion resistor in the pre-mag system introduces a voltage phase jump which can drive the main transformer into saturation. Inrush currents associated with the saturation excite low order resonances and can give rise to serious overvoltages that can have damaging effects for the equipment. Furthermore, thermal overloading of the equipment can be a consequence of the resonance excitation.

Based on the authors experience, systems with high-voltage feeder cables exceeding 50 meters in length and operating at primary side voltages above 100 kV are particularly prone to these issues, as confirmed in this study. The problem is not directly related to the cable length but is a result of the steady state design criteria for pre-mag systems that are typically used in the industry today. The design approach often results in pre-mag transformer ratings that form a low order resonance with the high voltage feeder cable for such lengths.

Proper system design is essential to prevent these challenges. The design process for pre-mag systems should include frequency domain and potentially EMT time domain analysis. Corresponding studies can be used to identify low-order resonances and predict resonant problems during energization. If such challenges are identified, increasing the kVA rating of the pre-mag transformer is a simple and effective mitigation strategy. Larger kVA ratings reduce the pre-mag transformer leakage inductance. This increases the resonance frequency, preventing its excitation by second and third order harmonic components in the inrush currents and providing additional thermal margins to accommodate harmonic power flows during energization. Optimizing the magnitude of the pre-insertion resistor is another possibility to reduce and limit resonant issues, as presented in this paper. Furthermore, the leakage resistance (X/R ration) of the pre-mag transformer can be increased to provide additional damping in the pre-mag circuit during the energization. This was not investigated in this paper, however, reduces overvoltages and can represent an alternative mitigation measure. The thermal energy absorption of the pre-insertion resistor is rather low, and the thermal capability of the resistor exceeds the absorbed energy by far as presented in this work. This can also be confirmed from various projects in which the authors were involved.

VI. CONCLUSIONS

Pre-mag energization systems offer an effective and robust alternative to controlled point on wave switching or high voltage pre-insertion resistors for large power transformers, where inrush currents and associated voltage variations need to be mitigated. The method is widely employed in remote offshore power systems, but also in onshore industrial power systems. Pre-mag systems are often designed based on steady state considerations only, neglecting resonant issues. The design approach can result in pre-mag transformer ratings that form a temporary low order resonance with the high voltage feeder cable during the energization sequence. These resonances can be triggered during the pre-mag energization, resulting in problematic resonant overvoltages and thermal overloading of equipment. These challenges can be prevented by proper system design that addresses resonant and transient phenomena, using frequency domain and EMT time domain investigations, in addition to steady state analysis. To mitigate low order resonances the pre-mag transformer kVA rating can be increased as outlined in this paper. With a properly designed system, pre-mag energization does not pose risks for the system and is a viable alternative for controlled point on wave switching or high voltage pre-insertion resistors for transformer inrush mitigation.

VII. REFERENCES

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