SF6 Generator Circuit Breaker Modeling

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Abstract - Generator circuit breakers are located between generators and step-up transformers in power networks and their ratings usually range from 100MVA to 1300MVA. Owing to the potentially high asymmetrical fault levels at relatively low voltage near the terminals of generators, the current interruption requirements of GenCBs are significantly higher than the distribution networks at similar voltages. Because of these high current rating properties, testing of GenCBs is costly and time consuming. Consequently, it is very useful to have valid computer simulations available.

In order to estimate the interrupting behavior of GenCB, a breaker model was developed in ATP/EMTP. The model incorporates arc voltages, escalation voltages and the reignition behavior of generator circuit breakers. The model was developed in EMTP by using MODELS and incorporates the four main stages of the breakers' operating processes: the closed contacts stage, the arc burning stage, the arc extinguishing stage and the opened contacts stage. The model was incorporated into a network simulation and the results were compared with IEEE Generator Circuit Breaker standards. More than sixty simulations have been done and Monte Carlo statistical studies were also carried out and the results are presented in this paper.

Keywords: EMTP, Generator circuit breaker, Arc voltage, System fed fault

I. Introduction

Generator circuit breakers are located between generators and step-up transformers in power networks. Because of the potentially high asymmetrical fault levels at relatively low voltage near the terminals of generators, the current interruption requirements of GenCBs are significantly higher than the distribution networks at similar voltages.

Modern GenCBs implement self-blast interrupting principles in order to reduce the operating energy of the circuit breaker. With this special design, GenCBs are capable of interrupting short circuit currents with high asymmetries. During a breaking operation by an SF_6 GenCB, the arc voltage modifies the behaviors of the short circuit current. Therefore, GenCBs usually exhibit significant arc voltages with short arcing times.

A few different mathematical circuit breaker models exist and are mostly characterized by experimentally measured parameters to describe the dielectric properties of different phenomena taking place in the breaker opening process. At the moment there is no existing precise universal arc model because of the complexity of the arc physics. On the other hand, most of the models mainly focus on describing the breaker behaviors during the current zero periods and ignore the importance of arc voltage.

The paper focuses on the modeling and simulation of arc voltages, escalation voltages and the reignition behaviors of generator circuit breakers. The model was developed in EMTP by using MODELS and incorporates four main stages of the breakers' operating processes: the closed contacts stage, the arc burning stage, the arc extinguishing stage and the opened contacts stage. Therefore, not only the dynamic conductances during current zero have been considered but also the effects of arc voltage on the arcing times have been included. The model was then tested in a representative network and the results compared with IEEE Generator Circuit Breaker standards. More than sixty simulations have been done and Monte Carlo statistical studies were also carried out and the results are presented in this paper.

II. Breaker Models

The proposed contact model is a black-box model with variable conductance. The value of conductance is determined by a mathematical model, which comprises four sub-stages: a closed breaker stage, an arcing burning stage, an arc extinguishing stage and an open stage.

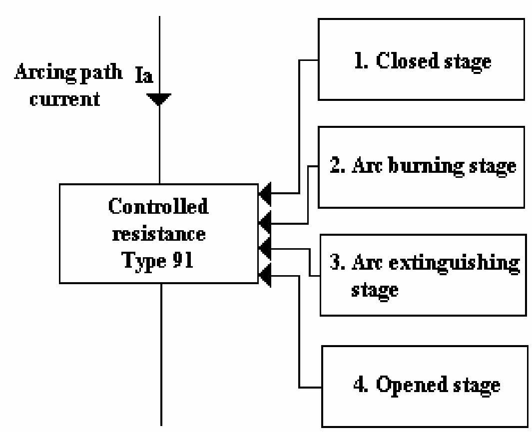

Fig. 1. Structure of combined model

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A. *Model of closed stage and opened stage*

A constant resistance with a value of 1μΩ is used for modeling the closed circuit breaker and constant resistance of 1MΩ is used for the open circuit breaker model after successful arc extinguishing.

B. *Model of arcing burning stage*

An arc model representing the voltage-current characteristic is used as in (1):

Arc voltage equation [1]: $U_{arc} = U_{oarc} \cdot C_{1arc} \cdot C_{2arc}$ (1)

Where

U_{arc} = arc voltage

U_{oarc} = 1000V

C_{1arc} = 0 for t<sta

C_{1arc} = (t-sta)/Tramp for sta<t<sta+Tramp

C_{1arc} = 1 for t>st+Tramp

$C_{2arc} = K\,(e^{(-(I/Io)2/2\delta)})+1$

Sta = instant of contact separation

I_o = current above which the arc voltage is constant

I = current flows through the contacts

During the simulation of the arc burning stage, current is imported to the model and the arc resistance R_{arc} is then calculated at every time step as demonstrated in figure 2.

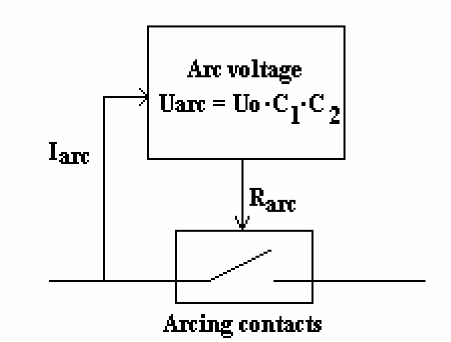

Fig.2. Model of arc burning stage

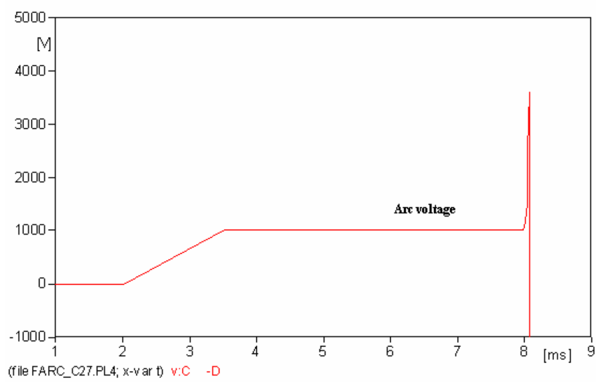

Fig.3. Arc voltage across the contacts

C. *Model of arc extinguishing stage*

A series connection of the Mayr and Cassie arc models is used to get a more accurate representation of the arcing contact during the arc extinguishing stage.

Mayr Theory [2]

$$\frac{1}{G}\frac{dG}{dt} = \frac{1}{\vartheta_m}\left(\frac{EI}{N_o} - 1\right)$$

$$\text{where} \quad \vartheta_m = \frac{Q_m}{N_m}$$

Cassie Theory [2]

$$\frac{d}{dt}G^2 = \frac{2}{\vartheta_c}\left(\frac{I}{E_o}\right)^2$$

$$\text{where} \quad \vartheta_c = \frac{Q_c}{N_c}$$

The total conductance of the arc model during this stage is calculated using (2) and applied in the simulation for the arc extinguishing stage.

$$\frac{1}{g} = \frac{1}{g_m} + \frac{1}{g_c} \qquad (2)$$

D. *Combined model*

The four sub-models form a combined contact model. Once the contact receives open signal, each sub-model is activated at the corresponding time. Figure 4 shows the result of combined arcing contact model.

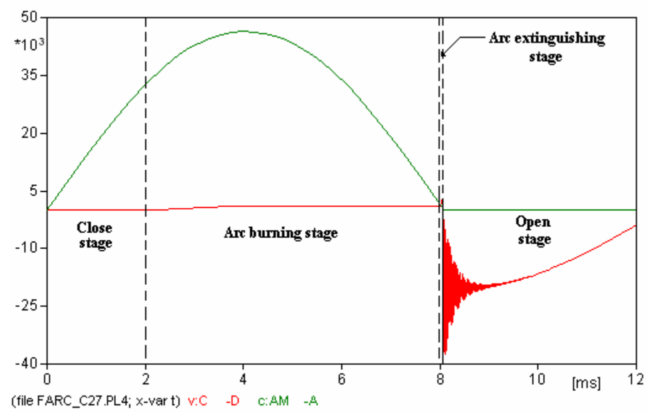

Fig.4. Individual stages of current interruption

E. *Determination of successful arc extinguishing*

After the contacts of the breakers mechanically open, the dielectric strength between them increases as a function of time, and a 'race' between the transient recovery voltage and the dielectric strength develops. At the current zero crossing, electrical arc is extinguished. However, it can be reignited if the dielectric strength between contacts is not high enough.

From [3], the value of 1MΩ was extracted as the limit value for successful arc extinguishing: if the resistance of the Mayr's arc model reaches this value, the arc is extinguished. On the other hand, if the resistance of the Mayr's arc model begins to decrease before this value is reached, reignition will take place and the arc will continue to burn until next current zero.

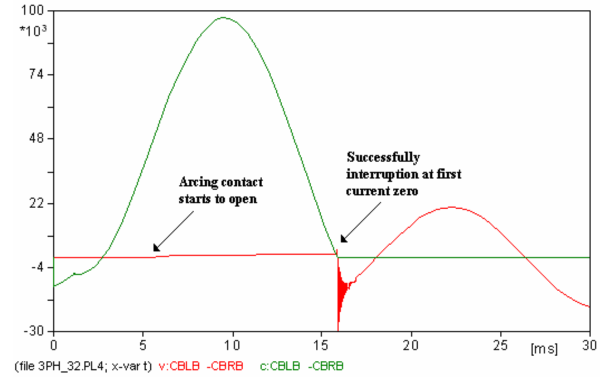

Fig.5. Successfully interrupts at first current zero

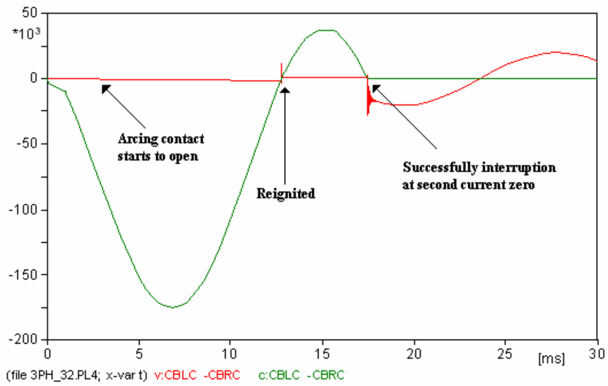

Fig.6. Successfully interrupts at second current zero

F. Effects of arc voltage

During a breaking operation by an SF_6 GenCB, the arc voltage modifies the evolution of the short circuit current. Therefore, GenCBs, which have a significant arc voltage have shorter arcing times.

Figure 7 shows the case without arc voltage implements in the breaker model while Figure 8 shows the case with arc voltage model. From Figure 7, the arcing times of phase A, phase B and phase C are 17.034ms, 15.335ms and 31.82ms respectively, while from Figure 8, the arcing times of phase A, phase B and phase C are 0.388ms, 10.242ms and 5.297ms respectively, which are much shorter than those without an arc burning stage model.

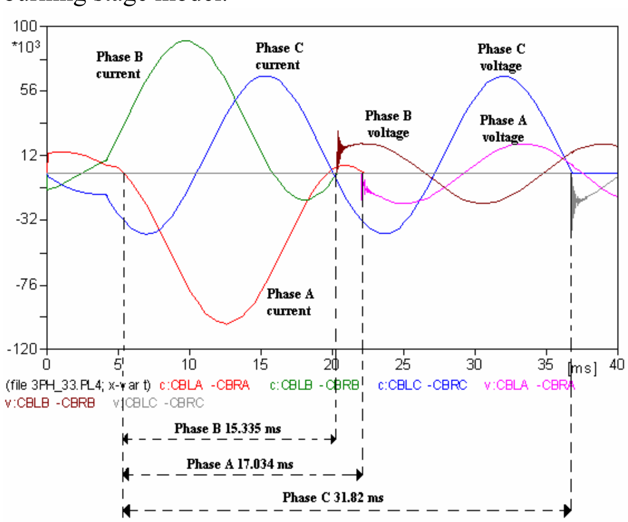

Fig.7. Currents interruption without arc voltage

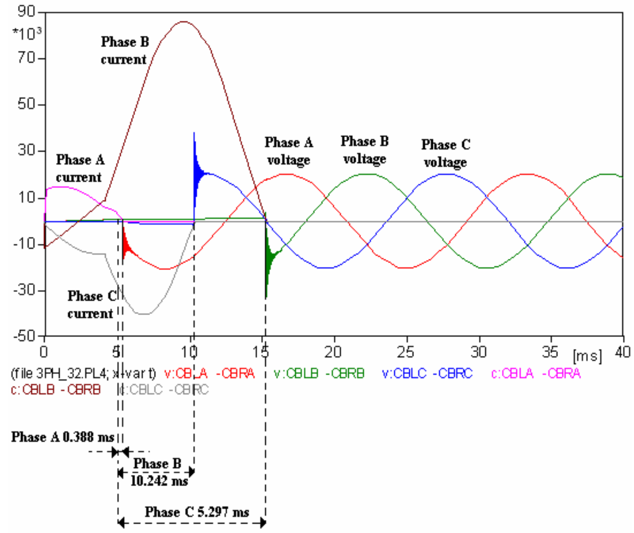

Fig.8. Currents interruption with arc voltage

III. Model Implementation

A. System Fed Fault [4]

Generator circuit breakers are located between generators and step up transformers. The faults which are fed by the system (or network) have the highest short circuit currents, combined with the most severe transient recovery voltages (TRV) applied across the breaker terminals at current interruption. Therefore, the contact model was first verified with system fed faults simulation network.

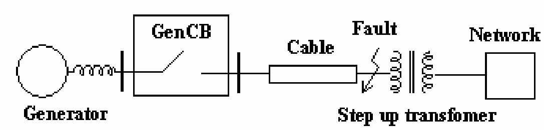

Fig.9. System fed fault of generator circuit breaker

B. Demonstration Circuit

Figure 10 shows the simulation network of a system fed fault. There is usually a cable connected between the GenCB and the step up transformer, hence the demonstration circuit comprises a voltage source, a GenCB, a cable and a fault initiated at the end of the cable.

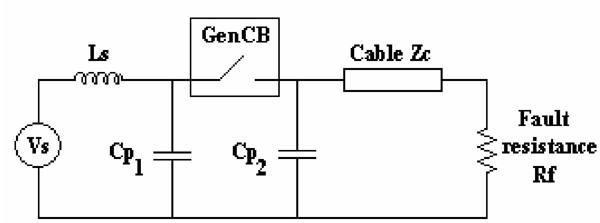

Fig.10. Demonstration circuit of system fed fault

TABLE I
MEAN AND 2% OVERVOLTAGES FOR DIFFERENT CASES

For a 60Hz, 25kV, 20kA source:	
V_s	20.4kV
L_s	1.914mH
C_{p1}	8.3nF
C_{p2}	9nF
Cable length	20m
Z_c	60Ω
τ_c	0.1us

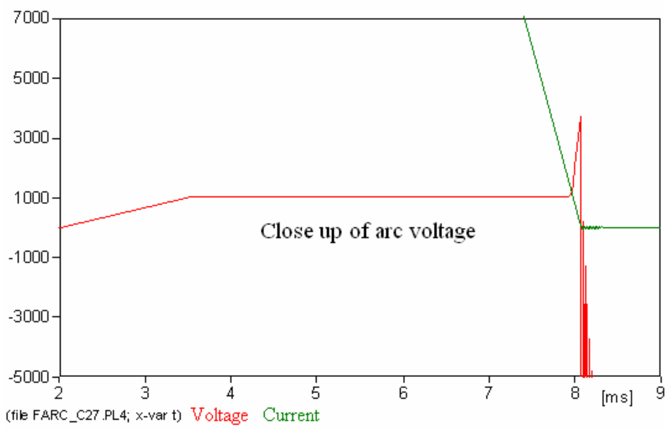

Fig.11. Close up of arc voltage develops across the contacts

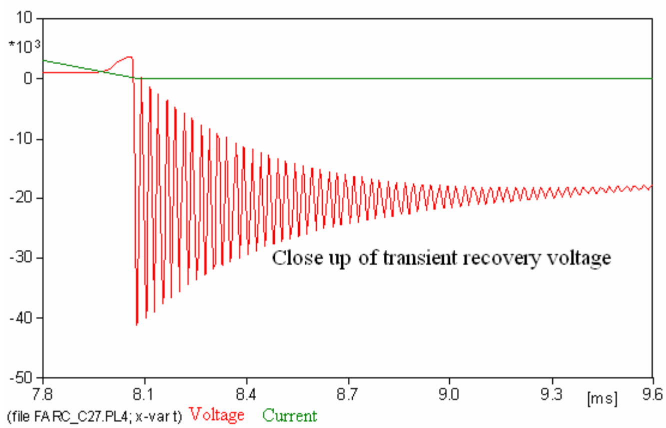

Fig.12. Close up of TRV develops across the contacts

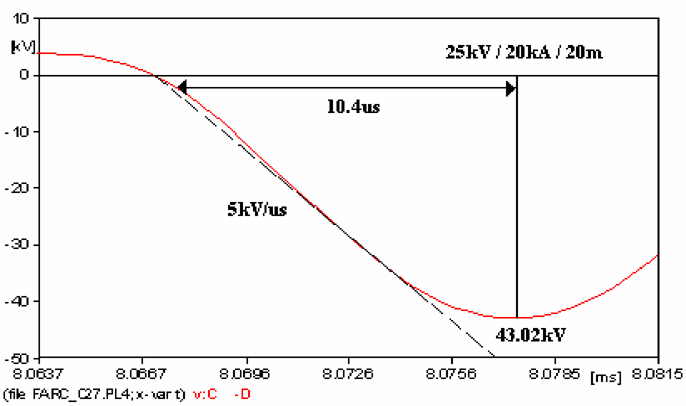

Fig.13. Rate of rise of recovery voltage and peak value (E2)

As shown in Figures 11, 12 and 13, immediately after current interruption at about 8ms, the voltage oscillates at a high frequency. This oscillation is a result of interaction between the source inductance Ls and the parasitic capacitance to ground Cp1. The frequency is given by:

$$f = \frac{1}{2\pi\sqrt{L_s C_{p1}}} \approx 40kHz \qquad (3)$$

The first TRV peak of oscillation reaches the value of 43.02kV and the rate of rise of recovery voltage is 5kV/μs. Following the decay of the transient, the voltage oscillates at 60Hz with 20.4kV$_p$.

More than sixty cases of system fed faults were tested using the simulation network. The system line voltage is 25kVrms and the fault current levels range from 20kA rms to 130kA rms, 60Hz. The results also show the transient recovery voltages (TRV) and rate of rise of recovery voltage (du/dt) of different cables length. The TRV results range 30kVpeak to 43kVpeak while the results of du/dt range from 3.6kV/μs to 5kV/μs. The T_2 values are around 10.5μs. It can be concluded that the arcing contact model simulated reasonable results which are comparable to IEEE standard C37.013 – 1997.

C. Application of the Arcing Contact Modeling

The performance of the breaker model in a typical application was evaluated using the generator network shown in figure 14. The voltage and current waveforms following disconnection of the generator are shown in figure 15.

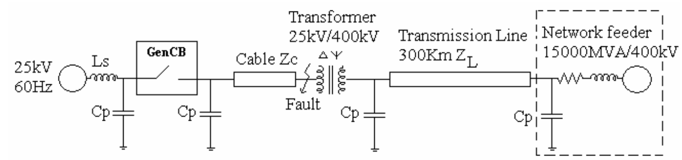

Fig.14. One-line diagram, Generator – GenCB – Cable – Transfomer – Transmission Line – Network Feeder

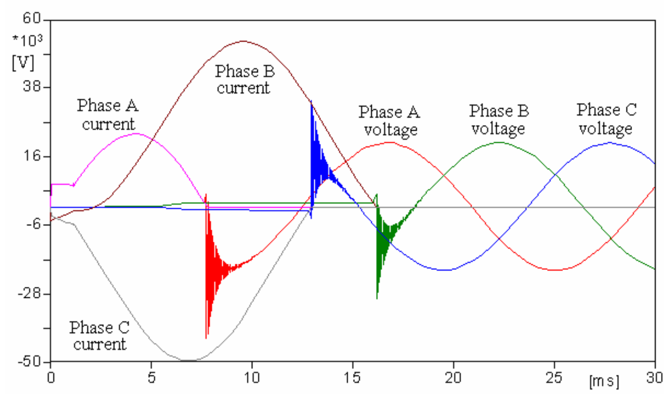

Fig.15. Overall current and voltage waveforms

The results show that the arcing times of phase A, phase B and phase C are 2.7517ms, 11.156ms and 7.955ms respectively. The TRV peaks of phase A, phase B and phase C are 42.23kV, 29.53kV and 34kV respectively. The rate of rise of recovery voltages of phase A, phase B and phase C are 4.02kV/μs, 3.75kV/μs and 3.78kV/μs respectively, which are comparable with the IEEE C37.013-1997 standard.

IV. Statistical studies

A Monte Carlo method was used to study the stochastic properties of breaker operations. A fault was initiated randomly at the end of the cable connected between the GenCB and the low voltage side of the transformer. The arcing contacts were assumed to be opened at a time 0.1ms, 0.15ms and 0.2ms following the moment of fault initiation. The arcing times and the TRV peaks were obtained. There was 50% probability of getting arcing times longer than 18ms, and 50% probability of getting reignition voltages higher than 1.56 p.u.

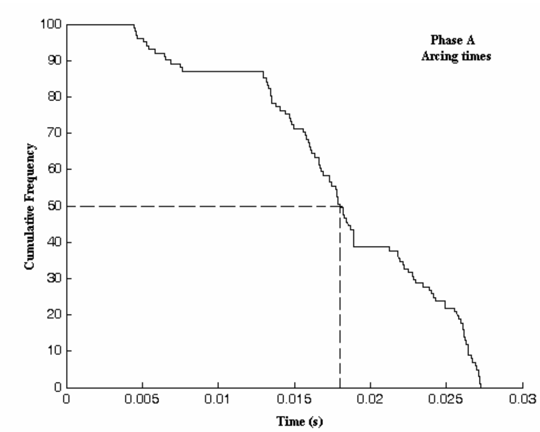

Fig.16. Cumulative frequency of arcing times, phase A

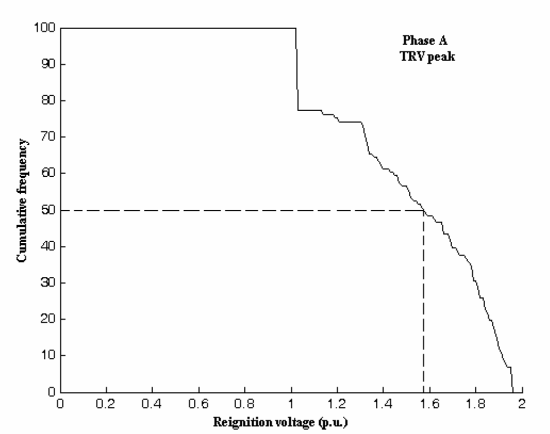

Fig.17. Cumulative frequency of reignition voltage, phase A

V. Conclusions

The paper presents the generator circuit breaker contact modeling in ElectroMagnetic Transients Program (EMTP).

A contact model which comprises four different breaker operation stages was presented. This model fully represents the dynamic and steady behaviors of a completely closed and opened breaker, as well as the burning phase and arc extinguishing phase when the breaker opening.

The model was verified on a representative network simulation and over sixty cases were carried out. The simulated transient recovery voltages are ranging 30kVpeak to 43kVpeak while the rates of rise of recovery voltages are ranging from 3.6kV/μs to 5kV/μs. The T_2 values are around 10.5μs. It can be concluded that the arcing contact model simulated reasonable results which are comparable to IEEE standard C37.013 – 1997.

The contact model was then verified using a real power system case. The effects of GenCB current interruption on the power network were also studied.

A Monte Carlo method was used to study the stochastic properties of breaker operations. It was shown that there is 50% probability of getting arcing times longer than 18ms and a 50% probability of getting reignition voltages higher than 1.56 p.u.

VI. Acknowledgment

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VII. References

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VIII. Biographies

S. Y. Leung is an MSc student in the Hong Kong Polytechnic University. She received her BEng (First Class Honor) in Electrical Engineering from the same University in 2003. Her research interests are EMTP simulation, and switching overvoltages.

L.A. Snider was born in Montreal. He received his B.Eng degree from McGill University, Canada in 1966, MSc and PhD degrees from the University of Birmingham, UK in 1969 and 1971. He is currently a visiting professor in the EECS Dept, Tulane University, USA. His research interests are in the area of power system real-time simulation, high-voltage engineering and insulation coordination.

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