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Secondary Arc Modeling
For Single-Phase Auto-Reclosing

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Outline

- Background
- What is secondary arc?
- Reclosing success factors
- Mathematical basis for modeling of secondary arc
- Arc extinction
- EMTP model
- General guidance

Background

- Most transmission line faults on solidly-earthed EHV systems are single-phase to ground
- Most of these faults are also transient in nature and not permanent
- Single-phase fault clearing and auto-reclosure using independent-pole circuit breakers can significantly improve reliability and lower risk of system instability
- Successful reclosure can be put at risk by prolonged secondary arcing

What is Secondary Arc?

- Heavy fault current arc produces a hot ionized channel in the air which remains momentarily after the main fault current is cleared by the opening circuit breaker
- Capacitive and inductive coupling from the healthy line phases sustains a “secondary” current arc in this ionized channel
- Usually self-extinguishes but if the faulted phase is reclosed before it extinguishes, the fault will re-establish resulting in an unsuccessful reclosure
- Prolonged delay (>2 sec) in reclosing to compensate for secondary arc extinction time can have adverse impact on system stability
- Compact lines vulnerable to long extinction times

Reclosing Success Factors

- Arc-extinction time is mainly a function of the secondary arc current
- Reclosing overvoltages have a significant effect
  - Trapped charge and fault location are important influences
- Secondary arc current is mainly influenced by phase-phase capacitance
- Compact lines and multi-conductor bundles have larger capacitances
- Conventional 500 kV line ~ 1.8 nF/km phase-phase
- Compact 500 kV line ~ 2.6 nF/km phase-phase

EMTP Modeling of Secondary Arc

- Interaction of Line and Arc has highly random properties
- Factors include
  - Impulse arc dynamic characteristics
  - Dielectric recovery properties of the air following partial extinctions (random effects like wind and thermal buoyancy)
  - Electromagnetic transients
- Specific arc model parameters sensitive to location, specific line geometry and length, and line voltage
- Arc parameters must be based on actual measurements for strict accuracy
- Generalized model only suitable for sensitivity analysis

EMTP Modeling of Secondary Arc

- The arc column energy balance equation is as follows:

$$\frac{dg}{dt} = \frac{1}{\tau}(G - g)$$

τ = arc time constant
g = instantaneous arc conductance
G = stationary arc conductance defined as:

$$G = \frac{|i_{arc}|}{(u_0 + r_0|i_{arc}|)l_{arc}(t)}$$

l_{arc} = instantaneous arc length
u_0 = characteristic arc voltage
r_0 = characteristic arc resistance per unit length

τ, u_0, and r_0 must be obtained from measurements

- Applies only to the high current arc and considers thermal reignition only – not dielectric restrike

EMTP Modeling of Secondary Arc

- The time constant of the arc is inversely proportional to the arc length and can be obtained from

$$\tau = \tau_0 \left[\frac{l_{arc}}{l_0}\right]^a$$

τ_0 = initial time constant
l_0 = initial arc length
a = a coefficient between -0.1 …. -0.6

- l_{arc} is the time-dependent dynamic length of the arc and is the most important parameter influencing the arc extinction and therefore the arcing duration

- It is highly dependent on random environmental factors including wind and thermal buoyancy and is therefore difficult to determine accurately

Arc Extinction

- The most challenging aspect of modeling secondary arc is the specification of the conditions for arc extinction
- Rapid elongation of the arc by air movement is the principle mechanism of spontaneous extinction
- Secondary arc elongation is given an initial strong start by strong upward movement of the primary arc plasma
- Wind has the same effect
- As the arc length increases so does its resistance and the arc current decreases
- The recovery voltage causes periodic reignition of the high resistance arc zones causing non-sinusoidal current waveshape

Arc Extinction

- As the length of the arc increases the fundamental component of the arc current decreases as an overall percentage of the peak arc current amplitude from the re-ignitions

- Arc extinction is immediately preceded by a short period of high amplitude peaks superimposed on the fundamental

- The re-ignitions excite travelling waves on the line with a period of twice the line travel time causing current pulses of this duration interleaved with current zeros that cause partial arc extinction

- Once the re-ignition voltage exceeds the recovery voltage the arc extinguishes

EMTP Modeling of Secondary Arc

- The model, although constrained by lack of strict accuracy, is useful for estimating worst case arcing duration and for studying the interaction between the system and the arc

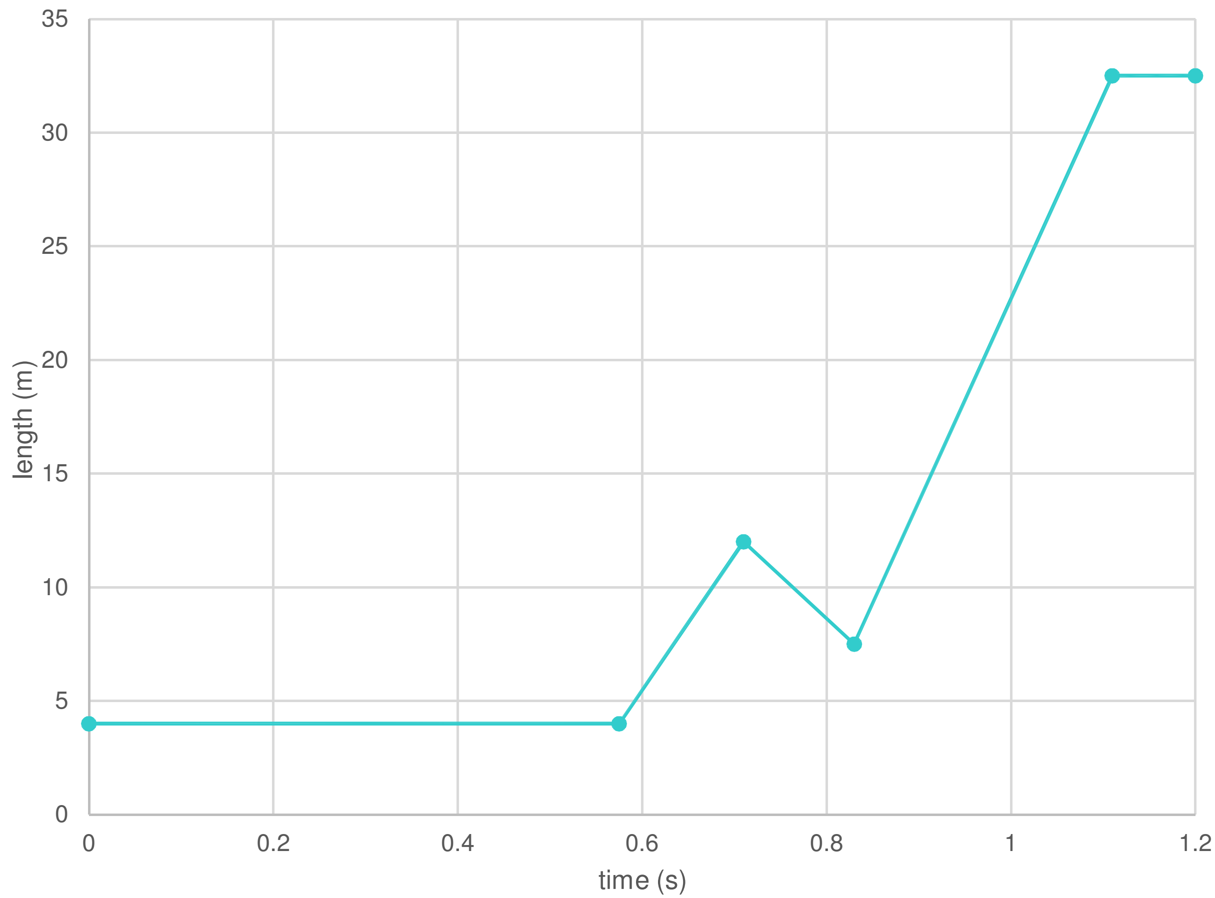
- Data must be obtained from measurements such as staged fault tests

- One such example is presented in the 2002 PSCC paper by Prikler, Kizilcay, Bán and Handl entitled “Improved Secondary Arc Models based on Staged Fault Tests” wherein 400kV parameters are derived:

$u_0 = 0.9$ kV/m $\quad\quad \tau_0 = 1$ ms $\quad\quad r_0 = 22$ mΩ/m $\quad\quad a = -0.5$

EMTP Modeling of Secondary Arc

- The time-dependent length of the arc was derived from observing the measured arc voltage and is shown here:



EMTP Modeling of Secondary Arc

- An extinction criterion is based on the time derivative of the instantaneous arc resistance exceeding a pre-determined value per unit arc length while at the same time the arc conductance is less than another predetermined value per unit arc length:

$$g_{min} = 50 \quad (\mu S \cdot m) \qquad \frac{dr_{arc}}{dt} = 20 \quad (M\Omega/(S \cdot m))$$

- This criterion does not take into account any dielectric restrike of the air but only takes into account the thermal extinction process

- Dielectric breakdown can be simulated by measuring the arc recovery voltage and comparing to a threshold restrike voltage and resetting the conductance to a post restrike value

EMTP Modeling of Secondary Arc

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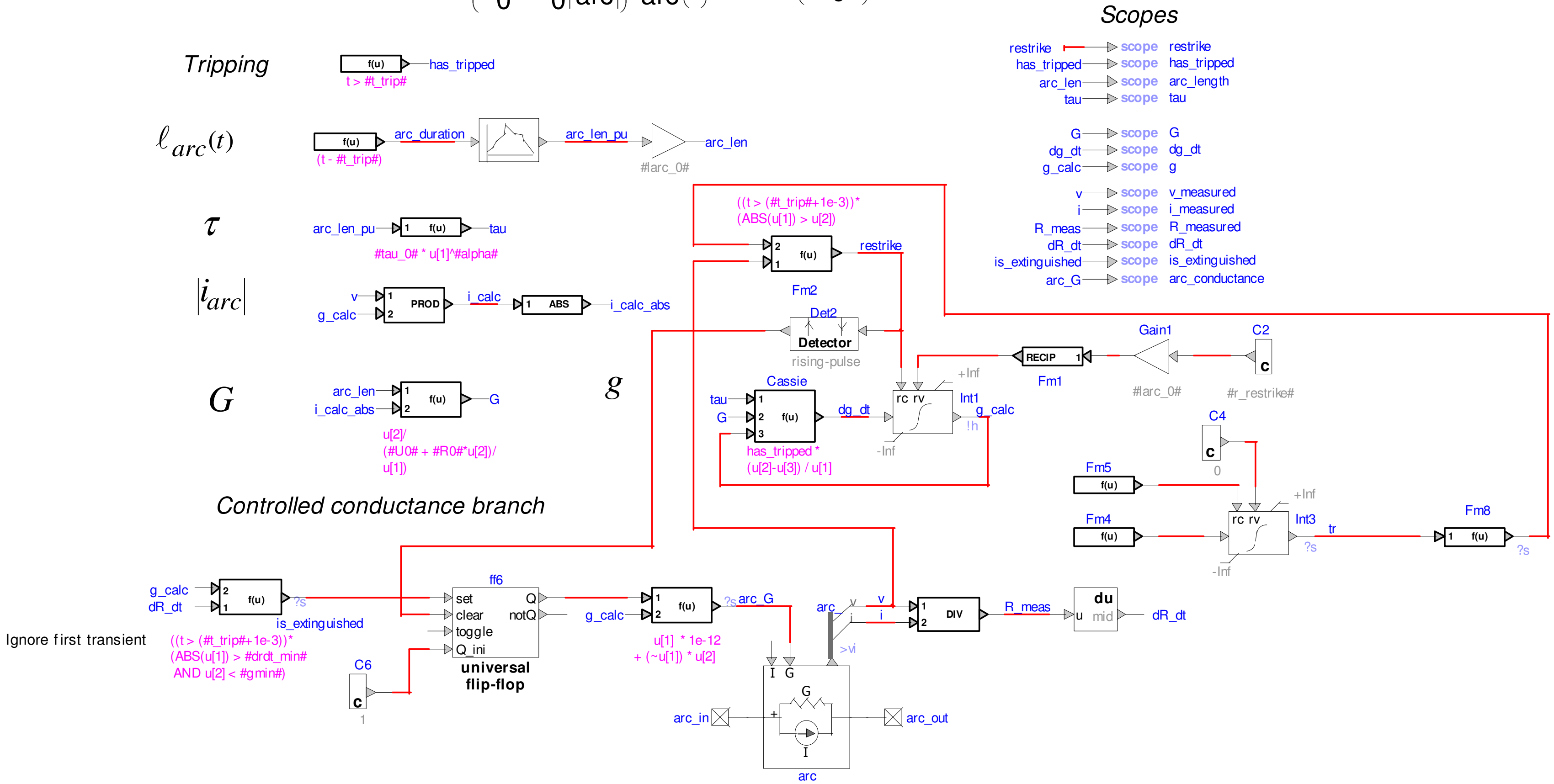
$$E_s \cong \frac{T_S}{T_0}\, e^{\frac{t}{\tau}}$$

Where: τ is the arc time constant
T_s is the ambient temperature
T_0 is the temperature of the arc channel at current zero
E_s is the electric field strength at temperature T_s

EMTP Modeling of Secondary Arc

$$g=\int\frac{1}{\tau}\left(G-g\right)dt$$

$$G=\frac{\left|i_{arc}\right|}{\left(U_0+R_0\left|i_{arc}\right|\right)\ell_{arc}\left(t\right)}\qquad \tau=\tau_0\left(\frac{\ell_{arc}}{\ell_0}\right)$$



Guidance Based on Experience

- If the ratio of the primary fault arc current to the secondary arc current is ≥ 50 the fast single pole auto reclose should be successful more than 90% of the time

- It is possible to successfully reclose with ratios less than this but the probability is reduced.

- The minimum primary arc path deionization time can be approximated by:

$$t = 175 + 0.5\,U_s \qquad (ms)$$

- The following table provides times for typical system voltages

U_s (kV)	Deionization Time (ms)
66	208
110	230
220	285
500	425

- In cases where recloseing is unsuccessful within an acceptably short reclose delay, 4-leg shunt reactors can be used to reduce the secondary arc current to permit more rapid auto-extinction

Discussion?