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DESIGN CRITERIA, STANDARDS & TESTING
FOR THE
SAGGING LINE MITIGATOR (SLIM)

Design criteria, standards and considerations for the SLiM device are listed in tables 1-5.

Table 1: List of environmental considerations for SLiM

Description	Min	Max	Typical	Issue	Notes
Ambient Temperature	-40°F	130°F	70°F	Materials	Current induced temperature not included. Maximum operating temperature 400°F
Wind Speed and direction	2.0 ft/s	176 ft/s	N/A	Vibration, Temp effect	Direction of wind with respect to conductor varies from parallel to cross-flow.
Seismic	N/A	0.45 g (H) 0.3 g (V)	N/A	Strength & Clearance	Per Uniform Building Code. Seismic loading may not be an issue.
Pollution (rain & pollutants)	Light – 16mm/kV	Heavy – 31mm/kV	Use Max	Insulating properties & Corrosion	For leakage length of line insulators. Frequency or amount of rain not needed – current regional selection tables are available with pollution and rainfall factors combined for selection of insulator design parameters.
Precipitation – Snow & Ice (Hoarfrost)	N/A	50mm Radius	N/A	Ice Loading	Max design parameter used for all cases where ice buildup is possible. Dimension given is for radius of buildup around conductor circumference.
Ozone	N/A	N/A	N/A	Corrosion/ Degradation	All components to be resistant to ozone attack.
Intensity of Solar Radiation (UV)	N/A	N/A	N/A	Corrosion/ Degradation	All components to be resistant to UV exposure.
Wildlife (animal contact, nesting, etc.)	N/A	N/A	N/A	Loading/ Corona/ Corrosion	Wildlife factors to be considered.

Table 2: List of mechanical considerations for SLiM

Design Condition	**Description**
Strength	Device components must withstand the ultimate tensile load of conductor. Also the strength of the splice joint attachment to SLiM must be considered for ultimate strength of device. Overall, SLiM is designed such that the device will not fail before the conductor.
Deformation	The only constraint is to maintain functionality of device during its intended design life.
Design Life	Serviceable Lifetime: Device should match industry standard for transmission line hardware. A target life span of 30-50 years is established for design.
Aging Mechanisms:	• <u>Corrosion/Material Degradation:</u> Caused by moisture, pollutants, UV, and ozone. Materials used in construction of device are corrosion resistant. • <u>Fatigue:</u> Device endures more than 500 full electrical current operating cycles (per IEC) – minimum to maximum loads caused by the conductors' expansion/contraction. Material of the device also comply with existing mechanical fatigue test and vibration standards. • <u>Creep:</u> Device, over its life span, does not fail or creeps such that it affects the ability of the device to function properly in mitigating the conductor sag. • <u>Wear:</u> Moving and contacting parts of the device engineered such that its functionality does not degrade over the life span of the device.

Table 3: List of electrical considerations for SLiM

Design Condition	**Description**
Corona Effect	Device design to limit electric field gradient to a maximum of 20kV/cm[1]. For 230kV and below voltages, the device is designed with "rounded" edges which satisfies this limit. For higher voltage lines (345kV and above), Corona rings will further limit electric field gradient to meet the above limit.
Current Flow	Device designed and constructed to withstands: • Nominal current flow of approx. 1400 A. • Short circuit current of 31.5 to 50 kA for ~6 cycles ≈ 100msec. • Asymmetric transient conditions of twice short circuit current for ~3 cycles.
Voltage & Frequency	Variations in voltage and frequency are minimal and have a negligible effect on the device. Therefore, these parameters need not be considered for design.
Magnetic Field	2-parallel conductors in-phase will repulse each other due to the magnetic fields created around each conductor. This force may have to be accounted for in SLiM device.
Lightning	A lightning strike to a tower can cause an arc to occur between the conductor and the tower over the insulator. This in turn creates two conditions for consideration: 1. The arc generates locally high heat that insulating components must not be susceptible to, i.e. thermal shock, melting, insulator surface degradation, or combustion. 2. The arc creates a short circuit condition in the conductor as described above. SLiM device is designed for short circuit conditions and can tolerate high temperatures.
Electrical Transients Magnification	The device was designed to ensure that it does not create a discontinuity in the impedance characteristics of the transmission line and, hence, cause magnification of switching or lightning induced electrical transients in the transmission system.
Fire	Wildfires in proximity to conductors can cause arcing to ground, as the combustion gases produce a conductive path to ground. This, in turn, creates a short circuit condition in the conductor. Device designed to tolerate high temperatures and short circuit conditions.
Insulation	N/A for the design of the device (no insulators).
Electrical Clearance	All clearances are kept within safety limits as published by industry as specified in Table 8.

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[1] Per "rule of thumb" used by utility engineers (Ref. 1)

Table 4: List of Emergency considerations for SLiM

Design Condition	**Description**
Tower Failure	It is known that at times conductors have supported a failed tower. Since the SLiM device is stronger than the breaking strength of the conductor, the SLiM device will not contribute to this failure scenario.
Line Disconnect	N/A as the device is made to be stronger than the conductor.
Vandalism (e.g. gunfire)	Device materials selected to minimize the susceptibility to damage from vandalism. SLiM design does not make it stand out as an 'attractive' target.
Force Majeure & Negligence	Reasonable effort used to consider any design parameters. However, it is not practical to design against an event that is completely undefined and unpredictable. SLiM's design and construction assumes reasonable care and prudent utility practice for installation and operation and maintenance.

Table 5: List of miscellaneous considerations for SLiM

Design Constraint	**Description**
Size	During the design phase, linemen were consulted to make sure the design allows for ease of handling and keeping minimum clearances during installation, operation, and maintenance.
Weight	In-Line: Device weight was considered for ease of handling for assembly, testing, shipping, and installation. The device does not create additional line sag or compromise the tensile strength of the conductor.
Performance	The device designed with enough degrees of redundancy such that the integrity of the line is not jeopardized upon failure of device components.

Summary of Requirements

Since the SLiM device is an overhead transmission line accessory, it meets the requirements and standards for such components. A review of standards for these components led to a list of the applicable Codes and Standards listed in Table 6 used in the design of SLiM. According to these standards the requirements for the design and testing of SLiM device include:

1. Size: The size of the device is such that it will meet all requirements for clearance during installation, maintenance, and operation. Also, size constraints for handling, installation and maintenance were observed.

2. Materials: Materials used for the device satisfy the design requirements. Specifically:
   - Strength: None of the components fail under cable breaking load (see #3)
   - Stiffness: Stiffness is such that device deformation does not prevent proper function.
   - Fracture Toughness: While only reasonable toughness was required, all materials used have very high fracture toughness and resistance, far in excess of common materials used for line hardware.
   - Corrosion resistance: Materials selected with extremely good corrosion resistance against environmental conditions – far superior to common materials used for line hardware.
   - Fatigue and creep properties: See items below in this section.
   - Electrical properties: Materials with appropriate electrical properties (e.g. resistivity and dielectric strength) are selected to meet the device's intended function.

   If a new material is to be developed for a component of the device, such material must be subjected to all required testing to demonstrate its compliance with the established criteria.

3. Breaking Load/Strength: The device shall meet the requirements of ANSI and/or IEEE Standard for Conductors (ASTM B232-74) and for Insulators.

4. Corrosion Protection: Not required as all materials used have very high corrosion resistance.

5. Connections:
   - Connections/joints carrying electrical meet ANSI Standard #C119.4 1991 for electric connectors.
   - Connections carrying mechanical loads meet the requirements of IEEE Standard #C135.61 1979 for line hardware testing.

6. Corona: The design of the device meets NEMA 107, CISPR 16-1 and CISPR 18-1 for Radio Interference Voltage (RIV) Performance of Line Hardware.

7. Vibration and Fatigue: The device design meets the IEC standard 61897 concerning the Stockbridge type aeolian vibration dampers or spacer damper.

8. Creep Strength and Deformation: No standards are available that apply to creep of line hardware. The materials used in the device are not susceptible to creep deformation or failure at operating conditions.

9. Live-Line Work Procedures: Since the device was designed to be installed while the line is energized, it satisfies the IEEE 516-1995 concerning maintenance methods on energized power lines.

Table 6: List of Codes and Standards Considered for SLiM Device

Standard #	Description
ASTM A-148	Standard Specification for Steel Castings, High Strength, for Structural Purposes
ASTM B-108	Standard Specification for Aluminum Alloy Permanent Mold Casting
IEEE C135.61-1977	Standard for the Testing of Overhead Transmission and Distribution Line Hardware
IEEE STD 516-1995	Guide for Maintenance Methods on Energized Power Lines
IEEE STD 1234-1997	Guide for Improving the Lightening Performance of Power Lines
ANSI C135.1-1979	American National Standard for Galvanized Steel Bolts and Nuts for Overhead Line Construction
IEEE STD 738-1993	Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors
ANSI C29.1-1982	American National Standard Test Methods for Electrical Power Insulators
ANSI C29.11-1989	American National for Composite Suspension Insulators for Overhead Transmission Lines-Tests
IEC TC 36B WG10 Project 1952	Composite Line Post Insulators for AC Overhead Lines with a Nominal Voltage Greater than 1000V
IEC TC 36 WG07 Project IEC 1462 Ed.1	Composite Insulators-Hollow Insulators for Use in Outdoor and Indoor Electrical Equipment
ASTM B232-74	Conductor breaking strengths
CEI Publication 815	Guide for the Selection of Insulators in Respect of Polluted Conditions
CEI IEC 61466-2-1998	Composite String Insulator Units for Overhead Lines with a Nominal Voltage Greater than 1000V
CEI IEC 61897-1998	Requirements and tests for Stockbridge aeolian vibration dampers
ASCE TK3242 G833 1991	Guidelines for Electrical Transmission Line Structural Loading
CEI IEC 383-2	Insulators for Overhead Lines with a Nominal Voltage Above 1000V Definitions, test methods and acceptance criteria
CEI IEC 826	Loading and Strength of Overhead Transmission Lines
CEI IEC 61284	Overhead Lines requirements and tests for fittings
ANSI C119.4 1991	Electric Connectors - Connectors for use between Al to Al or Al to Cu Bare overhead conductor
IEC CISPR 16-1 CISPR 18-2	Radio interference characteristics of overhead power lines and high voltage equipment
NEMA 107-1989	Methods of measurement of radio influence voltage (RIV) of high voltage apparatus
ANSI C63.2-1996	Electromagnetic noise and field strength instrumentation, 10Hz to 40Ghz specifications

Additional standards that were considered for SLiM Design:

ANSI / IEEE 935-1989	Guide on Terminology for Tools and Equipment to Be Used in Live Line Working
IEEE STD 539-1990	IEEE Standard Definition of Terms Relating to Corona and Field Effects of Overhead Power Lines
IEEE STD 563-1978	Guide on Conductor Self-Damping Measurements
ANSI C29.6-1977	American National Standard for Wet-Process Porcelain Insulators (High-Voltage Pin Type)
ANSI C29.7-1977	American National Standard for Wet-Process Porcelain Insulators (High-Voltage Line-Post Type)
ACE LWIWG-01 (91)	Suspension Composite Insulator Testing
IEEE STD 524-1992	Guide to the Installation of Overhead Transmission Line Conductors

LIST OF TESTS FOR SLIM DEVICE

SLiM has gone through extensive testing at a component level, prototype level and final pre-production design level. It has passed both laboratory and live-line tests.
A summary of the overall testing philosophy follows:

1. Functionality testing: This test aims to demonstrate the functionality of the device to control conductor sag. For this purpose two equal length conductors (front and back) will be installed between two poles with dead end insulators. Only one path will be equipped with the SLiM device. A current source of sufficient capacity will be used to vary the conductor temperature between the ambient to 100^{o}C. The conductor will be a common type used in 230kV lines. During the testing, line tension, sag, conductor temperature, and atmospheric conditions will be gathered.
2. Electric connectors testing: Since the In-line device will be installed in the same manner as a conductor splice, the current-carrying and mechanical performance must be checked. Five hundred full heating-cooling cycles will be applied to the device via an electric current per ANSI C119.4 standard.
3. Short circuit testing: As the device may be subjected to a line fault, it must resist, electrically and mechanically, an asymmetric short circuit current. Local and general current induced heating and magnetic forces within the device will need to be evaluated. A test procedure will be developed to address this requirement.
4. Breaking load testing: Once all other tests have been conducted, the device will be mechanically loaded until failure. This test will help establish the inherent safety factors and identify components that may require further improvement.

The SLiM has passed the tests listed in Table 7:

Table 7: List of Tests that SLiM has Passed

Test	**Description**
Prototype Testing	Research and development of SLiM included small-scale prototype testing to prove the feasibility of SLiM. Shape memory alloy used in the actuator was tested for both behavior and fatigue life. Extensive component testing on key components was performed. Functionality testing was then performed in a laboratory on a full-scale prototype.
Shape Memory Alloy Testing	The SLiM actuator is a key component and has passed extensive research and testing. The selection of the NiTI alloy was based on research and testing of 6 alloys for transformation strain, transformation temperatures, hysteresis, cyclic creep and cost. Fatigue tests were also performed on the two final alloy candidates.
Functionality Testing	Functionality testing was performed at Pacific Gas and Electric Company's Livermore testing facility to test the full scale prototype to prove that SLiM performs as designed and maintained full functionality in an environment that closely matched actual overhead transmission lines. SLiM's actual performance matched predicted performance.
Reliability Testing	Several reliability tests were performed on SLiM including: o) Short Circuit Test (40 kA (rms) – Tested per IEC at Kinectrics), o) Load test for mechanical load (> 49,000 lbs. (218 kN) – Tested per IEC at Kinectrics), o) Corrosion tests (tested for salt and acid environments at MIS), o) Electrically resistance and connectivity tests (Test at MIS),
Live-Line Test	SLiM has been installed on a San Diego Gas and Electric Company overhead transmission line since May, 2004. It was monitored extensively for performance as well as evaluated for ease if installation. Installation proved to be straight-forward. It has operated as design since installation. Upon removal by SDG&E, PTS will perform post-live line inspections on the SLiM device to examine the device for corrosion, fatigue, resistance and maintenance of functionality.

Test results are available on the PTS website: www.ptransolutions.com

Other Common Rules and Practices used by the Utility Industry and Considered in SLiM Design

As SLiM devices will be installed and maintained by the utility transmission line personnel, we identified and considered some general guidelines. These guidelines are defined based on common rules and practices exercised by linemen in Live Line Work. In general, the device should be designed to facilitate safe and convenient handling. For this purpose:

- The device should not be heavier than typical hardware and preferably should be portable by a small crew of linemen.
- The size of the device shall be such that the risk of reducing "approaching clearance" is limited. Furthermore, for portability purposes, the device shall be small enough to be carried by one lineman.
- The device should contain protective covers, rounded edges, etc. Handles and attachment points may be added to assist installation and maintenance. If appropriate, warnings will be posted or printed on the device.
- Finally, the installation of the device should not require de-energization of the transmission line.

TABLE 8: CLEARANCE REQUIREMENTS FOR OVERHEAD TRANSMISSION LINE COMPONENTS

Line voltage (kV)	Design Phase to ground clearance (m)	Minimum Design Phase to ground clearance due to the wind (m)	Design Phase to Phase clearance/Minimum (m)	Minimum Design Phase to Phase clearance due to the wind (m)	Minimum clearance for hot line maintenance (m)	Number of Insulator units/ gap distance of insulator string (m)
69	0.80	0.15	1.00/0.70	0.25	0.90	4 /1.06 or 4/1.12
120	1.20	0.30	1.60/1.10	0.50	1.15	6/1.68 or 7/1.778
160	1.50	0.35	1.90/1.50	0.60	1.35	8/2.24 or 9/2.286
230	2.00	0.45	5.00/1.90	0.75	1.70	10/2.80 or 12/3.048
315	2.30	0.60	5.00/3.20	1.00	2.15	14/3.92 or 16/4.064
735	6.00	1.40	12.00/10.00	2.30	3.95	28/7.84 or 33/8.382

Line voltage (kV)	Steady state Short circuit current Transient use a factor of 2 to 3 (kA)	Leakage distance (m)	Lightning insulation $1.1*(V_{50}-3\sigma)$ $V_{50}=530*d$ (kV)	Switching insulation (kV)	Power frequency insulation (kV)	Minimum conductor diameter (cm) $mm^2=0.5067$x MCM
69	32	1.16	350		140	0.65
120	40	2.11	550		230	1.50
160	31.5, 50	2.72	750		325	1.85
230	31.5, 50	3.92	950		395	2.77
315	31.5, 50	5.28	1175	850	450	2.54 x 2
735	40	12.24	2100	1425	830	3.56 x 4

Ultimate theoretical clearance

Line Voltage (kV)	Minimum clearance with wind (m)	Minimum clearance at rest (m)
69	0.03	0.35
120	0.10	0.62
160	0.15	0.85
230	0.24	1.28
315	0.34	1.87
735	0.88	5.47