Experiences and Challenges of Combined HV & EHV Qualifications to IEC, AEIC and IEEE 48 & 404

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ABSTRACT

This paper focuses on the issues associated with bringing one or more of the IEEE cable accessory standards into the AEIC / IEC combination approach for cable system qualification. It first highlights the similarities and differences associated with the testing methods, test limits, and number of components/lengths of cable required by each standard. NEETRAC's experience with the AEIC / IEC combination approach from 2005 – 2014 is then reviewed with respect to the overall failure rate of each component type. Finally, the risks / benefits of combined qualification programs containing either complex test loops (i.e. number of components) and / or combined standards requirements is presented.

KEYWORDS

Cable qualifications, cable systems.

INTRODUCTION

The use of XLPE cable systems continues to increase in the Americas due to the economies that are achieved and high reliability of modern installations. As use of these systems increases in the utility space, so do the importance of qualification procedures. Currently US utilities are comfortable with the cable system approaches implemented in the latest iterations of the AEIC (CS-9 2006) & IEC (60840-2011 & 62067-2011) standards. However, the IEEE standards (48-2009 & 404-2012) are still seen to have some benefit and are used in some applications.

As described in the last Jicable Conference the combined AEIC / IEC [2~~1~~] test approach (intercalation of the most searching/stringent elements of two separate standards) is well accepted by users. The use of the combined AEIC / IEC approach has led to the speculation that it may be possible to make further combinations, for example IEEE 48 [5] with IEEE 404 [6] or IEEE 48 & 404 with AEIC / IEC, etc. The attraction is the potential for reduced time and cost, on a per component basis, when compared with approaching the standards separately. Since Jicable11, the IEEE 404 standard was significantly updated; such that even if a combination may previously have been attractive, the current embodiments might make it much more difficult.

Thus, this paper focuses on the issues associated with bringing one or more of the IEEE standards into the combination approach. Each IEEE standard includes quite different test orders, philosophies on Pre & Post tests as well as requirements for test temperatures. Although, on paper, it is feasible to add an IEEE test to the well established IEC / AEIC combination (sometimes described as a *"Super Combo Test")* the technical elements are very stretching for the laboratory and cable system. Consequently, this presents an interesting Risk / Benefit optimization for those using this route. The optimization includes effects, which increase the risk, such as: number of cycles, likelihood of missed cycles due to the complexity of the requirements, increased number of accessories, elevated voltages, etc.

The paper focuses on three areas

1 Review of the current (2010 to 2014) test experience, similar to that previously reported by Pultrum et al [7] in CIRED09, with the combined (AEIC / IEC) and separate (IEEE) tests {to the recently revised standards}. The authors find higher success rates in tests than noted in those previously reported.

2 Consider the impact of the differing test factors in the standards (e.g. 2 h vs 6 h hold requirements for AEIC and IEEE, respectively, during load cycling) on test laboratories and cable systems. There will be particular focus on the impact of the temperature transients on accessories imposed by the required currents.

3 Use of available test experience (Figure 1) to quantitatively estimate the increased risks associated with added combinations of tests and components (i.e. typical 1-2 joints in IEC vs minimum of four required by IEEE), thereby more clearly understanding the value optimization scenario.

COMPARISON AND DEVELOPMENT OF COMBINED TESTS

Component vs System Style Tests

IEC adopts a cable system test approach requiring minimum quantities of cable and one of each accessory type to be included in the test. The user is then provided with some level of assurance that the whole system can work together. The IEC approach may conveniently be described as having three elements: Electrical Pre-Tests (PD and Tan δ), Load Cycle Tests, and Electrical Post-Tests (PD, Impulse, ac). There are optional Annexes, most commonly E & G that augment the main type test with assurance against water ingress for cable and joints.

IEEE and ICEA are component tests and only assign requirements to the specific component referred to in the specification, even though other components are required for the test. The user assumes that the component tests are sufficiently searching that when components are assembled in a utility system the components that may never have been integrated before will work reliably.

ICEA takes a similar elemental approach to IEC but without the Annexes.

The IEEE 48 approach may conveniently be described as having four elements: Electrical Pre-Tests (PD, Impulse, AC), Load Cycle Tests, Electrical Post-Tests (PD, Impulse, AC), and Leak / Pressure Tests. IEEE 404 is similar to IEEE 48 but ANSI connector and Submersion tests are substituted for the Leak / Pressure tests of IEEE 48 and Annexes E & G of IEC.

AEIC previously adopted the component route (ICEA plus IEEE) to achieve qualification. However, recent iterations of the standard have introduced and give increasing prominence to the system approach.

Thermal Cycling

There are differences between the qualification programs due to test order, tests required, and applied voltages. However, the focus of this section is on the more significant differences in the thermal side of the load cycling requirements. The various constraints are detailed briefly in Table 1.

Combining IEC and ICEA is relatively straightforward with the most challenging aspect being the management of the heating in hours 0 to 6 such that the requisite temperature window can be achieved. Clearly, the addition of the IEEE requirements is less straightforward. To develop a scheme that encompasses all requirements is theoretically possible and requires:

- Acceptance of higher temperatures for the IEC & ICEA portions due to the higher IEEE temperatures in regions without conduit – this would generally be recognised as making the test more searching.
- Development of a heating current / time profile that achieves the IEEE temperatures within 2 h.
- Development of a heating current / time profile that permits cooling to ambient within 16 h.
- A stable laboratory environment that permits 1 through 3 above to be achieved with a sufficiently high reliability that the system exposure to the elevated temperatures and voltages is not increased due to "lost" or "non compliant" cycles.

Table 1 Summary of Thermal Cycle Constraints segregated by specification

Constraint	IEC	ICEA	IEEE 48	IEEE 404
Number of thermal cycles	20		30	
Maximum Conductor Temperature	95 – 100	100 – 105		95 - 105
Temperature measurement Location	Hottest Point		Mid way between accessories	
End of Cycle Temperature	None		5 C of Ambient	
Time in temperature window	Any 2 hours	Hour 6 to Hour 8	Any 6	
Heating Time	8 hours		Undefined	
Cooling Time	16 hours			
Conduit	Permit	Require	Not Specified	

Although not explicitly stated by any of the specifications, any large combined specification loop will likely require a thermal model loop upon which to determine the correct conditions; rather than taking an expedient route of calculating the conductor temperature from the jacket temperature via a Neyer McGrath style calculation. This has been done in our laboratory for the requirements set out in Table 2. The results of the experimentation to establish a current / time recipe for the combined protocol is shown in Figure 1 with a more standard combined IEC / ICEA recipe in Figure 2.

Table 2 Critical Thermal Cycle requirements for a combined IEC / ICEA / IEEE test

Test Attribute	Requirement	Determining Standard
Number of thermal cycles	30	IEEE
Maximum Conductor Temperature	100 - 105	ICEA & IEEE
End of Cycle Temperature	5 C of Ambient	IEEE
Time in temperature window	6 hrs incl Hr 6 to Hr 8	IEEE & ICEA
Heating Time	8 hrs	IEC & ICEA
Cooling Time	16 hrs	
Conduit	Required	ICEA

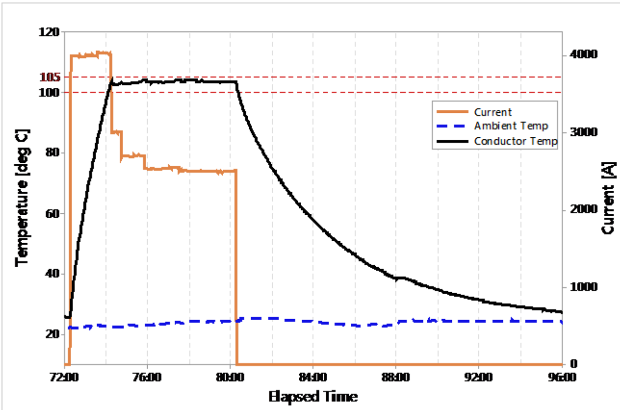

Figure 1 Current / time recipe for the combined protocol (Table 2)

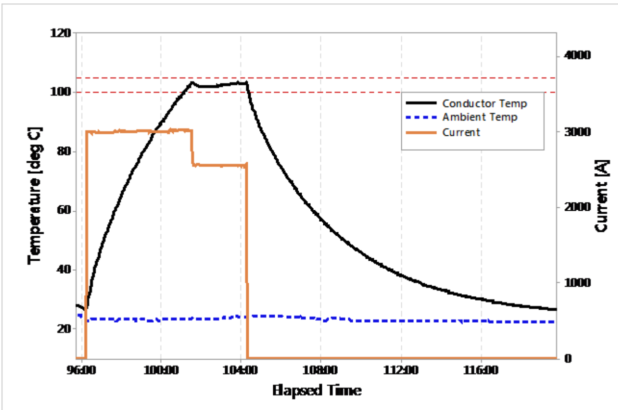

Figure 2 Current / time recipe for the combined IEC / ICEA protocol

A number of interesting findings arise from such investigations:

- The thermal model loop needs to be sufficiently large that it encompasses the different micro thermal environments prevalent in the main laboratory.
- The laboratory itself needs to be thermally stable and as practically draft free as possible.
- Multiple current steps are required within the recipe, thereby increasing complexity.
- The development time for the thermal recipes are two to three times longer than for the separate profiles.
- Very large (possibly un reasonably large) currents are required, thereby elevating the risks on the connectors and loading CT's.
- There is a significant risk of insufficient cooling, thereby leading to an upward drift in end point temperatures.
- The insertion of a joint, with temperature monitoring of the connector, in to the thermal model loop may be necessary.
- The thermal model loop may need to be run in parallel with the main loop (i.e. in "active" mode). This is to ensure that the main loop does not experience excess temperatures or ones that are too low. Low temperatures are a concern as they will cause the discard of a cycle and hence increase the voltage exposure. It is very likely that this will be required in any non climate-controlled laboratory.

AC Voltage Requirements

The combination of temperature and voltage defines the requisite load cycle. However in addition to the required temperatures, IEEE & ICEA also require a higher ageing voltage as compared to IEC (see Table 3). IEEE 404 has the additional requirement that the test voltage cannot be below the required value for longer than five minutes in a cycle.

Table 3 Summary of Ageing Voltage requirements segregated by specification

Constraint	IEC	ICEA	IEEE 48	IEEE 404
Ageing Voltage	$2U_0$	$2V_g$		
Application Requirement	Not specified			Cycle discounted if voltage < $2V_g$ for longer than 5 minutes

TEST LOOP ARCHITECTURE

The architecture of the test loop is determined in the specifications according to the requirements summarized in Table 4. The **bold** entries indicate the criterion that determines the overall architecture. The cable lengths required to manufacture the accessories are not included in the lengths shown.

The impact of these requirements can be seen by considering the simplest case for the standards of a single cable design, termination design and joint design.

Table 4 Summary of Test Loop Architecture Constraints segregated by specification

Constraint	IEC	ICEA	IEEE 48	IEEE 404
Min length of free cable between accessories	**5m**		2m	
Size of the required cable bend	**Depends on cable diameter**		None	
Min total length of cable required	**20m**			
Min bending radii of the cable	Manufacturer defined			
Minimum number of accessories to be tested	1 of each type		**2** **Terms**	**4** **Joints**

Clearly the footprint and construction burden of a combined test loop is significantly larger. A minimum length of 25 m of cable is required for the combined IEC / ICEA / IEEE compared to 10 m for the combined IEEE test. However, practical considerations for installation work, laboratory test components, and potential recovery options means that these minimum lengths are likely to be doubled in almost all practical implementations. Furthermore, not only are the loops longer in a combined test the number of accessories is larger; to achieve an IEC / ICEA / IEEE qualification on one design of joint, one design of cable and one design of termination requires the loop to have six accessories

TEST EXPERIENCE

It is known that not all Type Approval Tests for cable systems are successful. However, it can be difficult to gain an appreciation of the success rate as generally only the final successful test in the sequence is reported. Yet it is precisely this success rate that is required to make informed judgments on the risk associated with the likely outcome of particular tests. At CIRED in 2009, Pultrum et al [7] presented a useful discussion of the outcome of a wide range of MV, HV, and EHV tests. It was noted that the occurrence of failure is more likely in accessories than cable and that terminations have a higher likelihood of passing than joints. Our experience is confined to the HV and EHV arena and a more recent time frame (2005 to 2014). However, we are able to confirm the general findings from Pultrum et al in terms of the propensity for components to fail in a test.

Using the available data for combined IEC and ICEA tests we can estimate the "on test, per element" failure rates and their associated uncertainties. These findings for 2005 to 2014 are shown in Table 5. There are many ways to define a failure; the results in Table 5 represent Dielectric Failure, non-compliance due to not meeting the requirement of a measurement (ie PD, Tan Delta etc) are not included here. These data are derived from present day mature embodiments of accessory and cable technologies. They do not include tests undertaken in the development phases of products.

Table 5 Estimated Failure Rates for components in combined test programs

Component – Test	Mean Failure Rate (%)	Confidence Range on Mean Rate – 95% (%)
Cable – Type Test	5	1 – 29
Joint – Type Test	40	17 – 79
Termination (incl GIS) – Type Test	15	3 - 44

The data in Table 5 may be interpreted as follows: if 100 20 m cable lengths were tested to the IEC / ICEA protocol then on average we would expect 5 of these tests to result in failure. Similarly, an average 4 out of every 10 joints tested would be expected to fail. Although the rate is higher than for cable, the consequences are different. In many cases joint failure occurs early on in a test such that a replacement may be installed and the test restarted. An alternate interpretation of the result is, that with this level of risk in the IEC / ICEA scheme it would be prudent to install two joints (thereby increasing the chance that the minimum of one completes the test) with an effective Recovery Plan in place such that should a failure occur a repair may be affected so that the test plan may be completed. Furthermore, the reliability of components on type test may be ranked in terms of the likelihood of survival from Cable (8 times more likely to survive than a joint) through Termination (3 times more likely to survive than a joint) to Joint.

Of equal interest are the uncertainties of the failure rates. Clearly these add a level of "fuzziness" to any predictions that come from these data. Furthermore, these data clearly show that it is exceptionally difficult to use the results from Type Approval Tests (TAT) to definitively show that one system design or component is superior to another.

Table 5 shows the situation for dielectric failures; however the protection of the cable system from water ingress is also very important especially in tunnel and duct installations where the joint bays and manholes are often flooded. This has led to the use of the tests described in the IEC Annexes. The failure rates for these are shown in Table 6. Thus if a cable is required to comply with both an IEC type test and an Annex E test, (to assure a watertight & dielectrically capable cable) then the likelihood of passing both tests is 83%. Thus the water tightness technologies represent a very significant technical challenge.

Table 6 Estimated Failure Rates for water tightness tests

Component - Test	Mean Failure Rate (%)	Confidence Range on Mean Rate – 95% (%)
Cable – Water Penetration (Annex E)	11	<69
Joint – Test of Outer Protection (Annex G)	33	not determined

Our experience of IEEE 48 & 404 tests at HV & EHV is less extensive than with the combined IEC and ICEA tests; however the results suggest that the failure rates, on the same per component basis as those in Table 5, are somewhat higher. This is consistent with the increased minimum and actual exposures to cycles (30 vs 20) and higher and more extended temperature requirements. Similarly the results for PQ tests to IEC 62067 indicate lower rates; which are plausibly due to the lower electrical and thermal stresses in this long term test.

ESTABLISHING THE RISK / BENEFIT BALANCE

Clearly there are many perceived benefits of conducting combined tests compared to separate tests including reduced laboratory costs, shorter total test times, and lower installation and material costs. However, manufacturers and end users have multiple issues to consider when developing a qualification test program to suit their needs. The cost elements are easily computed and are not the prime focus of this paper. The Risk elements require experiential data and computation.

One qualitative element is that, generally speaking, in a combined test the whole test has to be completed to gain any of the standards included. Hence the benefit is real, but is only realisable once the test is complete (i.e. failure (as defined for Table 5) at IEEE accessory conditions does not permit the attainment of an IEC approval). The significance of this "all or nothing" issue depends upon the risk tolerance and experience base of the manufacturer.

The semi quantitative approach that we have taken when evaluating the risk is to compute the elements of the Total Risk and to visualise the components using a Risk Matrix. The computed components are Survival $_{\text{Architecture}}$ and Exposure $_{\text{On Test.}}$

Level of Risk

The Survival $_{\text{Architecture}}$ comes from the Architecture of the test loop (Table 4) and the Experience information (Table 5) such that

$$Survival_{Architecture} = \sum_{Cable}^{Accessories} (1 - Failure\ Rate)^N$$

Where

- Failure Rate is the estimated mean failure rate from Table 5
- N is the number of components (i.e. number of cable sections, joints, terminations) included in the test loop

Clearly, increasing the number of components or including components with higher failure rates will decrease the chances of survival. In addition, it will increase the chances that repair / recovery will be required. These estimates have been made for simple test architectures (Table 7): A & B architecture for IEC system tests, C & D architecture for IEEE component tests (note that although cable and terminations are required their survival is not critical to the component approval) & E architecture for combined IEC system & IEEE component tests.

Table 7 Survival $_{\text{Architecture}}$ estimation for selected architectures

	A	B	C	D	E
Cable Section	1	2	-	-	1
Termination	2	2	2	-	2
Joint	1	2	-	4	4
Survival **Architecture** {upper & lower limit} **(%)**	77 40	63 23	94 72	47 13	44 1

The estimations in Table 7 can be interpreted that between four to eight problem-free IEC system tests (case A) can be expected for every 10 undertaken. The likelihood of a problem-free test decreases quite rapidly with complexity (cases B, D & E). This does not necessarily mean that tests need to be abandoned when a problem occurs as the minimum number of units surviving differs between specifications. However, it does mean that Laboratories and Manufacturers need to be increasingly prepared with a Recovery Plan as the complexity increases. Additionally, the original architecture needs to be designed such that the Recovery can be affected easily. In general, this means having longer cable lengths than the minimum and having spare accessories available on site.

Risk Exposure

The previous section uses data from the 20 cycle IEC / ICEA tests to quantify the survival performance of individual components. The compliment to this in the risk framework is the amount of time that the chosen architecture is exposed. Hence the need to consider the Exposure $_{\text{On Test}}$, which comes from the required number of Thermal Cycles and the Cycle Reliability. The number of required compliant thermal cycles is set out in Table 2. Unfortunately, as the current / time recipe increases in complexity, it is more likely that cycles are "lost" and have to be repeated. Thus, the test loop will see more cycles than the required minimum. In addition, the longer the test the greater the likelihood that a power outage or equipment failure may occur, thereby further increasing the number of lost cycles.

Table 8 Estimates of Exposure $_{\text{On Test}}$ for selected specification combinations

	Min Number of Cycles	Reliability Multiplier	Exposure On Test
IEC / ICEA	20	1.1	22
IEEE	30	1.2	36
IEC / ICEA / IEEE	30	1.3	39
IEC / ICEA then IEEE	20 30	1.1 1.2	58

Our experience to date is that test reliability adders for cycles are of the order of 1.1 & 1.2 for IEC / ICEA and IEEE protocols, respectively. This means that it is likely to require 36 total cycles to achieve 30 IEEE compliant cycles. We would estimate that for an IEC / ICEA / IEEE combined test the multiplier would be of the order 1.3 to 1.4. Thus the Exposure $_{\text{On Test}}$ estimates are shown in Table 8. These results represent our direct and indirect experience. However it is possible that these might be under estimates, especially for the combined embodiment of the IEEE test.

Total Risk

In principle, it should be possible to combine the level of risk and the exposure mathematically and the authors are working towards this. However at the present time, the authors find it useful to represent the elements graphically and they have found that such a representation is sufficient to provide input to the discussions of the Architecture and Complexity. Such a graphical representation is shown in Figure 3. The representations for cases C to E are conservative estimates, with the outcome likely to be lower. This is because the estimates were derived from the wealth of IEC / ICEA tests which employ lower exposures.

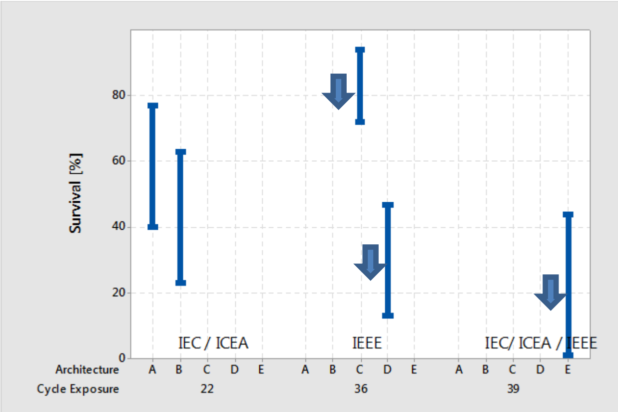

Figure 3 Total Risk Representation incorporating Exposure on Test and Architecture Risk

CONCLUSIONS

Not only do combined tests increase the risk via the architecture and the exposure, they increase the consequences of a failure as the combination requires an intercalation of the test order such that there are no interim success / approval points; they tend to be all or nothing. As a result in all the cases we have looked at over the last three years, there has not been a set of circumstances where the benefits of a combined IEC / ICEA / IEEE test program are commensurate with the risks that are incurred.

The benefit / risk balance is much more favourable for combinations of IEC / ICEA or IEEE 48 & 404.

It is not uncommon for test programs to include previously qualified components. Equally it has been known for these to incur failures which are unexpected given that they had passed at least one of the prior attempts. These events can cause considerable consternation. However, as has been shown here the outcome of type tests has a probabilistic element and this needs to be considered when a) developing the framework for test programs and b) placing successes / failures in context.

Although undoubtedly troubling, failures within type test programs, if they can be collated, represent a very good means by which to improve cable system technology.

Furthermore, additional / repeated successful type tests are an efficient way to improve the confidence and understanding of utility users in evolving cable systems.

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