Test Fixture to Apply DC Bias and AC Ripple Current for Reliability Testing of Electrolytic Capacitors

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***Abstract*— Electrolytic capacitors are widely used in the DC link of variable frequency drives (VFDs). Their reliability has a significant impact on VFD performance and life time. Typically, the life time of electrolytic capacitors is specified in vendors' datasheets at the rated continuous DC voltage and at the rated ripple current at one fixed frequency, under rated temperature and humidity conditions. In order to analyze and verify their life time, a test fixture is needed to apply both adjustable DC bias voltage and AC ripple current at a specific frequency.**

In this paper, a portable test fixture with low kVA requirements is proposed for electrolytic capacitor reliability testing. The test fixture can easily be scaled to test large capacitors with high ripple current rating. Multiple capacitor samples or entire capacitor bank assemblies used in VFDs can be tested. Design details of the test fixture and reliability test results are provided.

Keywords—Electrolytic capacitors; reliability; test fixture; VFD

I. Introduction

The reliability of electrolytic capacitors significantly impacts the lifetime of variable frequency drives (VFDs) [1-5]. Therefore, it is critical to ensure that the desired life time can be obtained from them under specific application conditions. Capacitor manufacturers specify life time as a function of applied DC voltage, RMS ripple current at a specific frequency (typically 100Hz or 120Hz), ambient temperature and relative humidity [6]. End of life is based on either an increase in equivalent series resistance (ESR) or decrease in capacitance from the nominal values at specific operating conditions.

One simple approach to determining useful life time is to test electrolytic capacitors at rated DC voltage, rated temperature and humidity. This method only requires a DC power supply with very low power requirement, to source the leakage current. However, the results will be conservative as there is no self-heating due to ripple current. A method to test with DC bias and AC ripple only at power line frequency was proposed by Amaral [7].

There are commercially available test equipment that can apply DC bias voltage and AC ripple current to test capacitors under the conditions specified on the datasheet [8, 9]. A simplified schematic of one such equipment is shown in Fig. 1 [8]. These test equipment are very well suited for low voltage rated electrolytic capacitors (<100V) and with low ripple current rating (<30A). Capacitors can be connected in series or parallel to allow simultaneous testing of multiple capacitors. The main disadvantage of these test equipment is that they are inadequate for testing high voltage (400-575V) and high ripple current rated electrolytic capacitors used in VFDs. There are commercially available linear power amplifiers [9] that can be used to apply DC bias voltage and AC ripple current, using the schematic shown in Fig. 2. The drawback of this approach is that the power output is dependent on output impedance and special measures (impedance matching transformers) are required to make them work for testing capacitors.

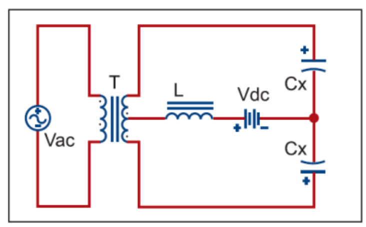

Fig. 1. Schematic of commercially available AC ripple current test equipment [8]

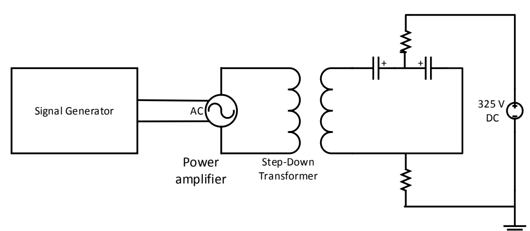

Fig. 2. Power amplifier based test set-up to test capacitors with DC bias and AC ripple current

Capacitors can also be tested in a VFD itself as this simulates the exact conditions that they will be subjected to in an application. In the method proposed by Hasegawa [11], only the high frequency component of the capacitor ripple current is included; since, the line frequency harmonics are not included, this method will result in inaccurate lifetime estimates.

The objective of this work is to build a test fixture with the following characteristics

- Adjustable DC bias voltage, and AC ripple current magnitude and frequency.
- Capability to test high voltage and high ripple current electrolytic capacitors used in VFDs.
- Scalable to test several capacitors or capacitor bank assemblies
- Portable with low kVA requirement.
- Low THD AC ripple current.
- It is also desirable for the fixture to provide AC ripple current as a superposition of multiple frequencies with independently adjustable magnitudes, to more closely simulate real life applications.

A new test fixture that meets the objectives defined above has been designed, built and tested. Preliminary experimental test results are provided to demonstrate that the fixture complies with the requirements to test electrolytic capacitors used in VFDs. This paper also provides one reliability test result for commercially available electrolytic capacitors.

II. TEST FIXTURE DESIGN

A. Test Fixture Schematic

The schematic for the test fixture developed is shown in Fig. 3. It consists of two sub-systems – one provides adjustable DC bias voltage, and the other provides adjustable AC ripple current and frequency.

Sub-system #1 provides DC bias voltage and consists of an auto-transformer, a bridge rectifier and DC bus capacitance, which generates an adjustable magnitude and stiff DC voltage (impervious to AC line harmonics) to the electrolytic capacitors under test. Since, this sub-system only provides DC leakage current to the capacitors under test, it has very low kVA requirements and could be powered by either a single-phase or a three-phase supply.

Sub-system #2, which provides adjustable AC ripple current, consists of a VFD with an output sine-wave filter [10] and a step-down isolation Δ-Y transformer. The test capacitors are connected as a three-phase Y-network, with the DC bias voltage connected between the neutral of the test capacitor network and the neutral of the Δ-Y transformer. A very low AC voltage is required at the secondary of the isolation transformer to drive the ripple current. Therefore, the kVA requirement at the input to the VFD is low. Thus, the overall fixture requires very low kVA and can be made portable.

The VFD is operated in adjustable voltage mode at the desired AC ripple current frequency i.e. the output voltage is ramped up from zero to a desired value with the frequency held constant. Thus, the VFD operates as an adjustable AC power supply. The isolation transformer is required to prevent circulating currents between the two sub-systems.

Sub-system #1 is designed to provide up to 1150V of DC bias voltage. This allows testing of capacitor bank assemblies typically used on 690VAC rated VFDs. The bridge rectifier is rated at 2200V peak inverse voltage. The DC bus capacitance consists of 2 electrolytic capacitors in series, each rated for 575VDC. The auto-transformer is rated for 480VAC input, 0-960VAC output and 1.5 kVA. If an auto-transformer is not available with a high output voltage, the desired output voltage can be obtained using the method shown in Fig. 4, where the auto-transformer is rated for 480VAC input, 0-480VAC output, and the isolation transformers provide a 1:1 transfer ratio.

Sub-system #2 consists of a 480V VFD, a sine-wave filter rated for minimum VFD PWM frequency of 4 kHz, and 10:1 step-down transformer (480VAC input, 48VAC output, frequency up to 120Hz). The step-down ratio can be selected based on the maximum capacitance and ripple current of the capacitor assembly under test. Similarly, the transformer frequency rating can be specified based on test requirements. Typical control transformers are only available as single-phase units with rated frequency of 50/60 Hz; therefore, a custom

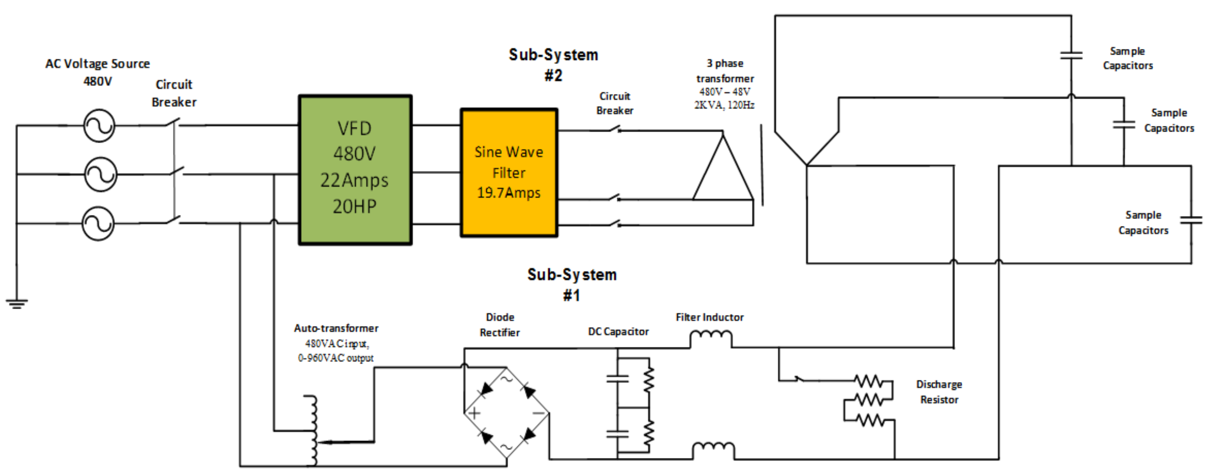

Fig. 3. Proposed test fixture to generate adjustable DC bias voltage, and AC ripple current magnitude and frequency.

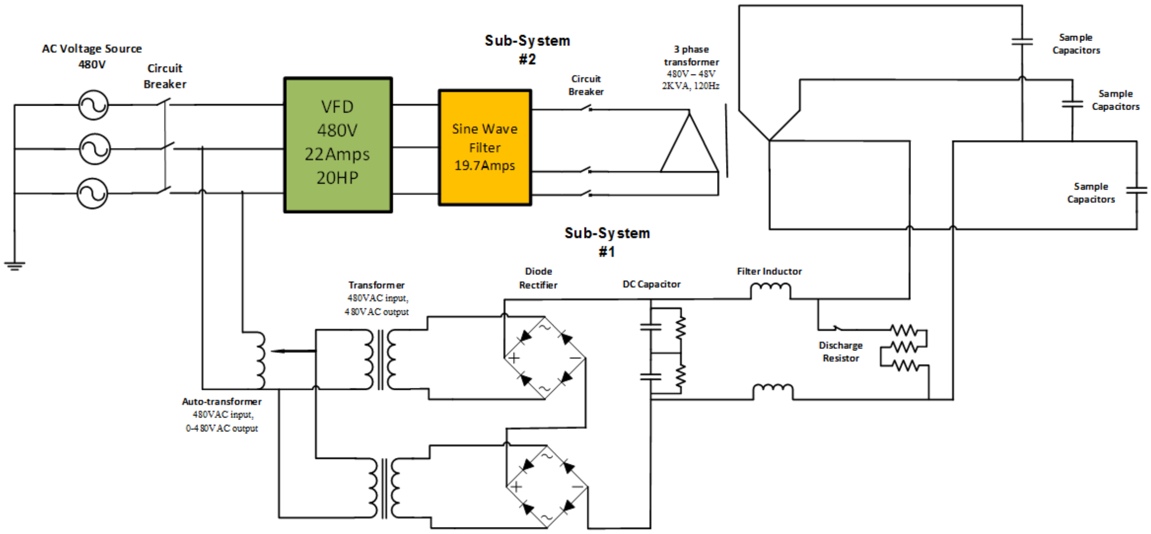

Fig. 4. Method to generate high AC voltage from a lower AC voltage auto-transformer.

design is required for a three-phase unit with higher rated frequency.

B. KVA Requirements and THD

To estimate the kVA required for the test fixture, an example is provided. Consider a typical high capacitance and high ripple current capacitor used in a VFD, with capacitance of 10,000 µF, 400VDC and 30A of ripple current at 120Hz. To test a total of 12 capacitors simultaneously (4 in parallel per phase on the output of the isolation transformer in sub-system #2), the source power requirement is about 1.5 kVA. The 12 capacitors represent the DC bus capacitance typically used on three 200HP, 480VAC VFDs, with a total source power requirement of about 600 kVA. This demonstrates that the test fixture kVA requirement is a very small fraction (<< 1%) of the rating of the VFD in which the capacitors are used.

To obtain low THD capacitor ripple current (at 120Hz ripple current frequency), the VFD PWM frequency can be set to about 4-8 kHz. Since the kVA requirement is low, a higher PWM frequency can be used without any concerns about current de-rating even with a small VFD rated at about 5 kVA.

The proposed test fixture design can be easily scaled for high ripple current requirements, to allow testing of several capacitor bank assemblies.

If it is desired to test the capacitors with ripple current that consists of the superposition of several different frequencies with arbitrary current magnitudes, the VFD can be programmed to output voltage waveforms that consist of multiple frequencies with independently adjustable amplitudes.

III. Experimental Tests

The test fixture shown in Fig. 3 was built to test three capacitors rated at 9700 µF, 400VDC, 35A ripple current at 120Hz. Tests were conducted with AC ripple current frequencies of 60Hz and 120Hz, and with VFD PWM frequencies of 4 kHz and 8 kHz. The datasheet value of ripple current rating at 60Hz is 27A. The DC bias voltage was adjusted such that the peak voltage (DC + AC ripple) across the test capacitor was 400V.

Waveforms of the applied voltage and the ripple current through each capacitor are shown in Figs. 5-7 for the different test cases. The THD of the AC ripple current applied to each capacitor are listed in Table I. Clearly, <5% THD can be obtained. Thus, the waveforms are suitable to use for the purpose of determining the reliability of electrolytic capacitors.

A. Experimental Tests Waveforms

In Figs. 5-7 below, the top waveform is the voltage across the test capacitor (50V/div), the middle waveform is the current through the test capacitor (20A/div) and the bottom waveform is the line-line voltage on the primary side of the 3-phase isolation transformer in Fig. 3 (100V/div).

The time scale for the plots is 10 ms/div in Figs. 5-6 and 5ms/div in Fig. 7.

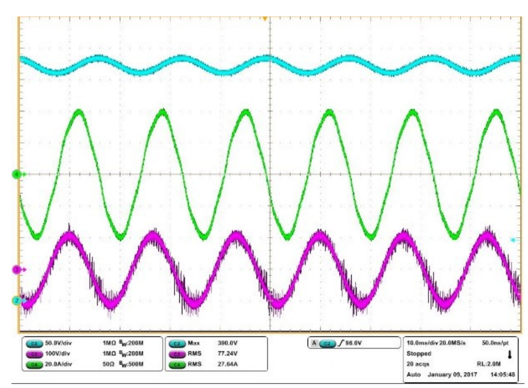

Fig. 5. Test capacitor voltage and current waveforms: 400VDC, 60Hz, 4 kHz PWM, 28A ripple current.

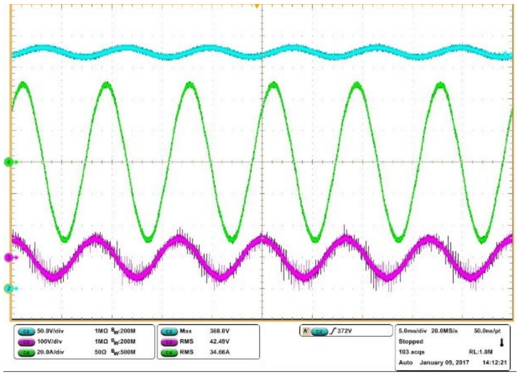

Fig. 6. Test capacitor voltage and current waveforms: 400VDC, 120Hz, 4 kHz PWM, 35A ripple current.

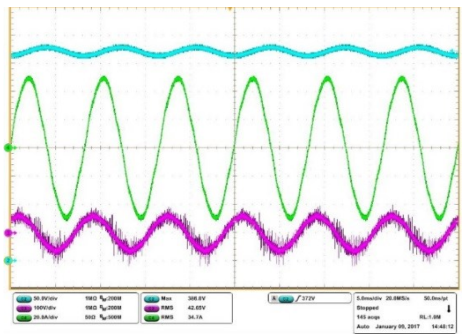

Fig. 7. Test capacitor voltage and current waveforms: 400VDC, 120Hz, 8 kHz PWM, 35A ripple current.

B. *Experimental Tests THD*

TABLE I. TEST CAPACITOR RIPPLE CURRENT THD

Experimental Tests Results		
PWM Frequency	***Ripple Current Frequency***	***Ripple Current THD***
4kHz	60 Hz	4.15%
4kHz	120 Hz	2.48%
8kHz	120 Hz	3.21%

IV. RELIABILITY TESTS

Lifetime testing on 12 samples of 400VDC, 800µF ± 10% rated capacitors has been completed using the fixture based on the schematic of Fig. 3. The test fixture and thermal chamber are shown in Fig. 9. DC voltage bias of 400V and rated AC ripple current of 2.7A RMS at 120Hz were applied to the capacitor samples of Fig.8, and at constant ambient temperature of 105°C provided by the thermal chamber. Measurements of capacitance, ESR and leakage current for 9 samples were taken at regular intervals and are listed in Table II - IV. Capacitance and ESR are measured at 120Hz, 20°C. Leakage current is measured at 400VDC bias. The lifetime of the capacitor as specified on the datasheet is 5000 hours, when subjected to the rated voltage, ripple current and ambient temperature.

The manufacturer's guideline specified the life time criteria.

a) Capacitance: Within ±20% of the initial value.

b) ESR: Not more than 200% of the specified value.

c) Leakage Current: Not more than the specified value.

The initial value of capacitance is 718µF, and the 5000hours capacitance measurement is 715µF, within ±1% of initial value; The 5000hours ESR measurement 147mΩ is still lower than specified value of 324mΩ; The final leakage current is 40µA which is much lower than specified value of 1718µA. The samples passed the 5000hours life time test.

TABLE II. ELECTROLYTIC CAPACITORS RELIABLITY TESTING MEASUREMENT DATA OF CAPACITANCE

Samples	*0 Hours* Capacitance (uF)	*650 Hours* Capacitance (uF)	*1600 Hours* Capacitance (uF)	*2600 Hours* Capacitance (uF)	*3500 Hours* Capacitance (uF)	*5000 Hours* Capacitance (uF)
1	720	728	723	724	722	716
2	711	719	714	715	712	706
3	720	728	723	724	723	718
4	712	719	715	715	712	706
5	722	731	726	727	725	719
6	720	728	723	724	722	716
7	722	731	726	727	725	718
8	721	730	725	726	724	718
9	718	727	723	723	721	715
Ave	**718**	**727**	**722**	**723**	**721**	**715**
Variation	**0.00%**	**1.16%**	**0.49%**	**0.60%**	**0.31%**	**-0.53%**

TABLE III. ELECTROLYTIC CAPACITORS RELIABLITY TESTING MEASUREMENT DATA OF ESR

Samples	*0 Hours* ESR (mΩ)	*650 Hours* ESR (mΩ)	*1600 Hours* ESR (mΩ)	*2600 Hours* ESR (mΩ)	*3500 Hours* ESR (mΩ)	*5000 Hours* ESR (mΩ)
1	70	83	85	105	120	143
2	72	82	89	106	125	153
3	70	79	84	101	113	132
4	70	83	88	107	124	152
5	70	83	89	108	121	148
6	71	84	91	108	124	151
7	71	81	86	103	122	151
8	67	80	84	101	115	138
9	66	82	87	109	124	151
Ave	**70**	**82**	**87**	**105**	**121**	**147**
Variation	**0.00%**	**17.54%**	**24.88%**	**51.20%**	**73.52%**	**110.37%**

TABLE IV. ELECTROLYTIC CAPACITORS RELIABLITY TESTING MEASUREMENT DATA OF LEAKAGE CURRENT

Samples	*0 Hours* Leakage Current (uA)	*650 Hours* Leakage Current (uA)	*1600 Hours* Leakage Current (uA)	*2600 Hours* Leakage Current (uA)	*3500 Hours* Leakage Current (uA)	*5000 Hours* Leakage Current (uA)
1	64	43	39	40	34	35
2	55	33	35	40	24	33
3	59	32	38	38	33	36
4	49	32	45	35	37	38
5	44	42	34	33	37	39
6	51	44	41	32	34	40
7	52	30	34	34	49	42
8	59	44	35	40	40	47
9	49	39	29	43	34	45
Ave	**54**	**38**	**37**	**37**	**36**	**39**
Variation	**0.00%**	**-29.67%**	**-31.54%**	**-30.50%**	**-33.20%**	**-26.35%**

V. CONCLUSIONS

Electrolytic capacitors are one of the most critical components used in VFDs and their life time has a significant impact on overall VFD life time. Therefore, it is important to test these capacitors for their reliability under specific operating conditions.

In this paper, the design for a test fixture was proposed that provides the capability to adjust DC bias voltage and AC ripple current magnitude and frequency. The fixture meets the design objectives of being scalable to test high capacitance and high ripple current capacitor bank assemblies used in VFDs, with low THD AC ripple current, while being portable and with low input kVA requirements.

Preliminary experimental results and details of reliability testing of commercially available electrolytic capacitors were provided to demonstrate that the fixture meets the design objectives for reliability testing of electrolytic capacitors. ESR and capacitance measurements, before, during and after the lifetime testing with DC bias and AC ripple current, are provided to validate the design of the test fixture and demonstrate its significance for reliability testing.

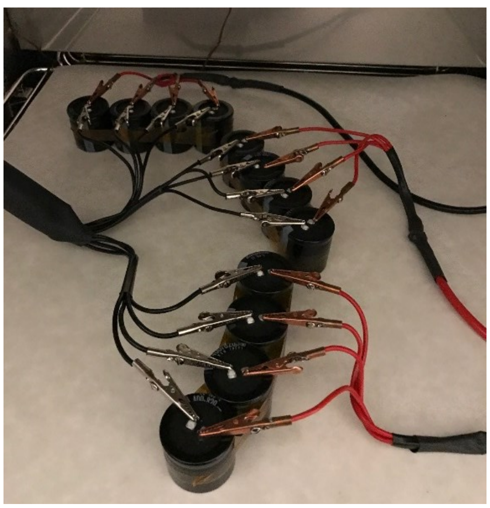

Fig. 8. Capacitor Samples under rated voltage and rated ripple current, placed in a thermal chamber to provide rated ambient temperature.

Fig. 9. Test Fixture and thermal chamber

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