M4140 Capacitor Bank Testing Application Note

This application note discusses using the M4100 and the M4140 clamp-on CT probe to test individual capacitors in a capacitor bank without disconnecting them from the bank.

For this application, the M4100 serves solely as the measurement instrument. The power source is the M4110, which provides much higher AC output (up to 25 A). The M4100 monitors the voltage supplied by the M4110 through the red low-voltage (LV) lead. The M4100 measures the current drawn by the individual capacitor through a clamp-on CT probe connected to the blue low-voltage lead.

Advantages of using this application of the M4100 to test capacitor banks are:

- Does not require disconnecting each capacitor unit from the bank, reducing test time.
- Each capacitor unit test takes about one minute to perform.
- Provides more effective troubleshooting of high-voltage AC capacitors than a low DC voltage capacitance test.
- Test conditions and test data are automatically recorded and saved. This greatly facilitates data analysis, management, and exchange, and avoids human error.
- A comprehensive bank of test data and conditions (voltage, current, watts loss, power factor, capacitance, correction factors, temperature, humidity, date and time) is essential for comparison and trend analysis.
- For M4100 users, this test requires little investment and further enhances the usefulness of the M4100.
- The M4110 affords extensive control and protection of the external source voltage.

The capacitor bank test has been used to successfully troubleshoot an intermittent voltage unbalance and assess the condition of capacitor banks [1, 4]. The test procedure and interpretation are simple and can be easily implemented in a maintenance program or used for troubleshooting.

This test cannot detect fluid leaks in early stages that have not affected the capacitor's internal condition. Visual inspection is the best technique for this problem.

Requirements

Hardware:

- M4100 instrument
- M4140 Capacitor Bank Test Kit (clamp-on CT probe and lead)
- M4110 Leakage Reactance Interface

Software:

- M4000 software with M4120 External Reference Module, version 2.1 or later

Test Principle

The M4110 applies an external source voltage to the capacitor bank (Figure 5 through Figure 8). The M4100 measures the test potential and individual cell current magnitude and angle (angle reference to the applied voltage). From this data, the software extracts the electrical parameters (voltage, current, watts, % PF, and capacitance) for each individual cell and displays it on the External Reference screen of the M4000 software. The changes in % PF and capacitance indicate the change in condition of the capacitor.

The current of each capacitor I_i is measured through the clamp-on current probe (Figure 1), which is connected to the M4100 via the blue LV lead (Figure 6). The test voltage is measured via the red LV lead through the M4110 Red terminal (Figure 6). The M4100 determines the watts loss, power factor, and capacitance of each tested capacitor using the measured voltage, current, and phase angle between the voltage and current, in the same manner as in power factor testing [2].

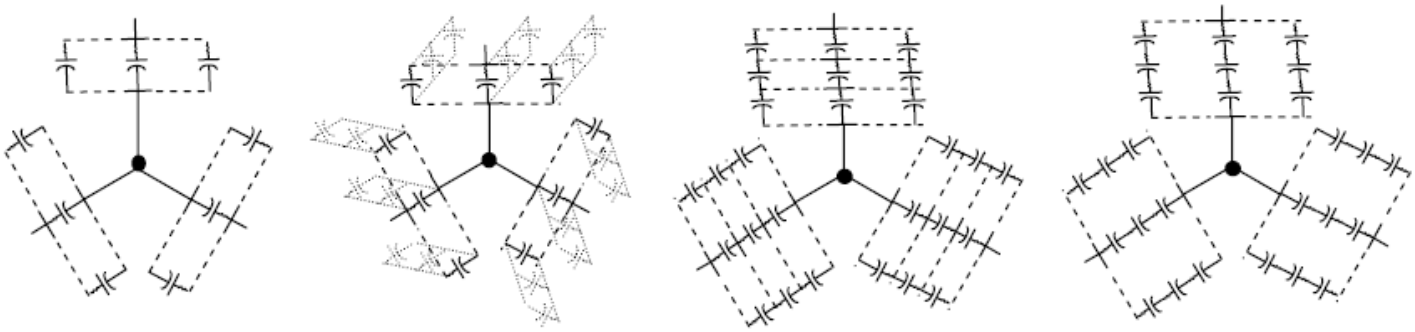
Figure 1. Clamp-on Current Probe (Rated 600 V) Connected to Blue LV Lead

Capacitor Bank Assembly and Unit Identification

Assembly

A capacitor bank is typically assembled in one of four possible arrangements: simple parallel group (Figure 2a), multiple parallel groups (Figure 2b), series-parallel groups (Figure 2c), or serial string groups (Figure 2d). Normally, a capacitor group consists of four to twenty capacitors mounted in parallel in the same rack. Therefore, they are

subjected to the same voltage. Then the group can be connected to other groups, to form multiple parallel or series-parallel groups. They can also be connected in a serial string in different racks, and then the strings are connected together in parallel (Figure 8 through Figure 10 and Figure 2d).



(a) Parallel Group **(b) Multiple Parallel Groups** **(c) Series Parallel Groups** **(d) Serial String Groups**

Figure 2. Capacitor Bank Configuration

Unit Identification

Parallel Group

For a parallel group, we use *Xn* to identify the group and *Xn-m* to identify a unit in the group, where:

X = phase identification (ex. A, B, and C)

n = rack position starting from the line end to neutral for series-parallel groups or from top to bottom starting from the outside rack for parallel groups

m = unit position in the rack, starting from left to right when facing the capacitor rack

Serial String

For a serial string, we use *Xk-n* to identify a string in the group and *Xk-n-m* to identify a unit in the string, where:

X = phase identification (ex. A, B, and C)

k = position of the string group

n = string position in the group, starting from the current-transformer side

m = unit position in the string, starting from phase end (top) to neutral end (bottom)

Figure 3 and Figure 4 are examples of capacitor identification for a capacitor bank that consists of five-series parallel groups.

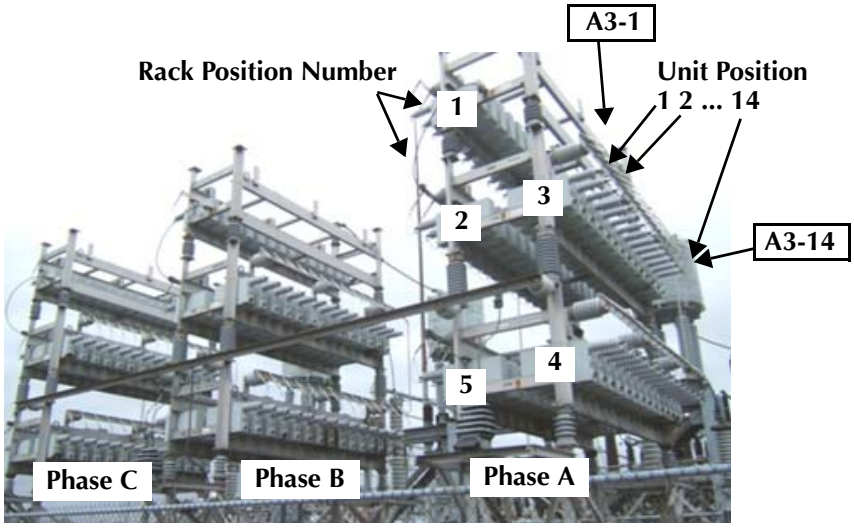


Figure 3. Five Series-Parallel Groups

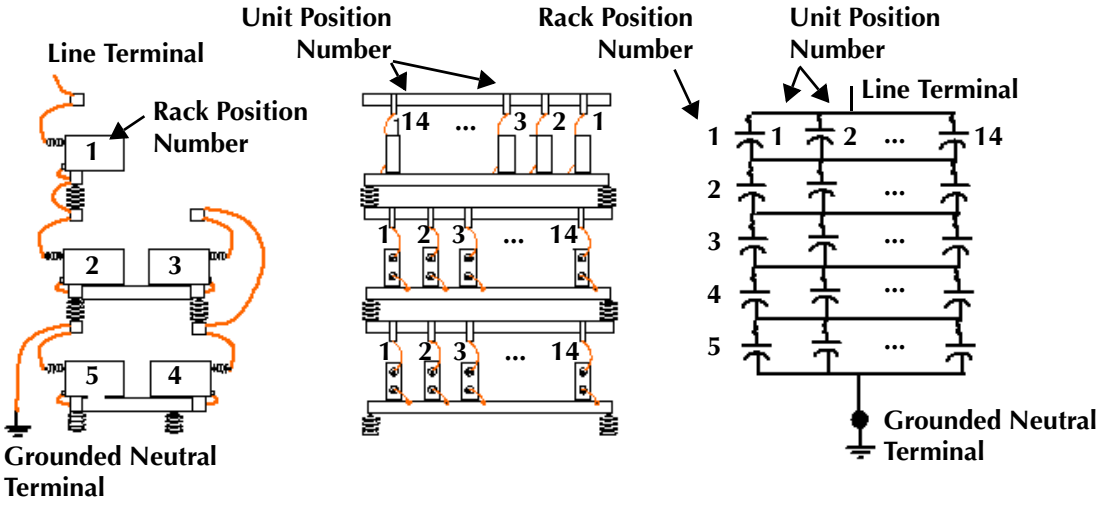


Figure 4. One Phase of the Five Series-Parallel Groups

Test Procedures

WARNING

Before attempting to test a capacitor bank, establish a safety procedure that complies with your policies, standards, and regulations. Isolate, ground, and discharge the capacitor bank.

Parallel Group

To test a unit in a parallel or series-parallel group: Move the current probe from unit to unit until the end of the group (Figure 5 and Figure 6). The same process applies to each group for multiple parallel or series-parallel groups (Figure 7).

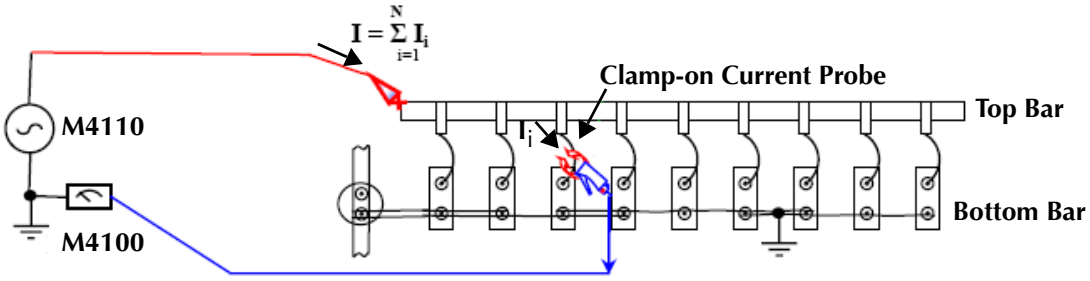


Figure 5. Test Principle for a Unit in a Parallel Group

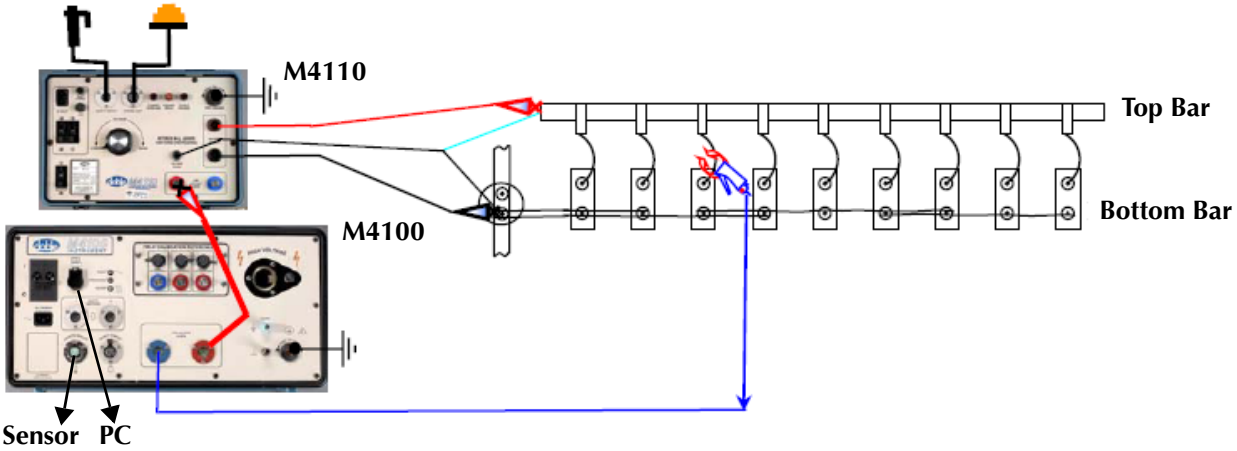


Figure 6. Test Connection for a Unit in a Parallel Group

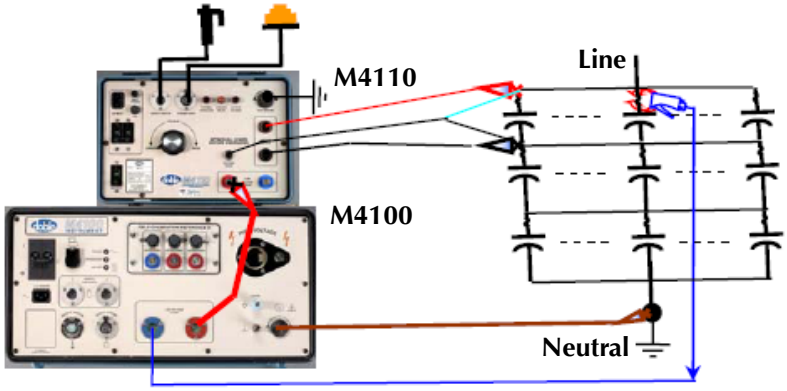


Figure 7. Test Connection for Multiple Series-Parallel Groups

Serial String

To test an entire serial string: Move the current probe from one string to the next until the end of the group (Figure 8). The same process applies to each string in the group.

To test a unit in a serial string: Move the Voltage Sense lead from unit to unit until the end of the string (Figure 9 and Figure 10).

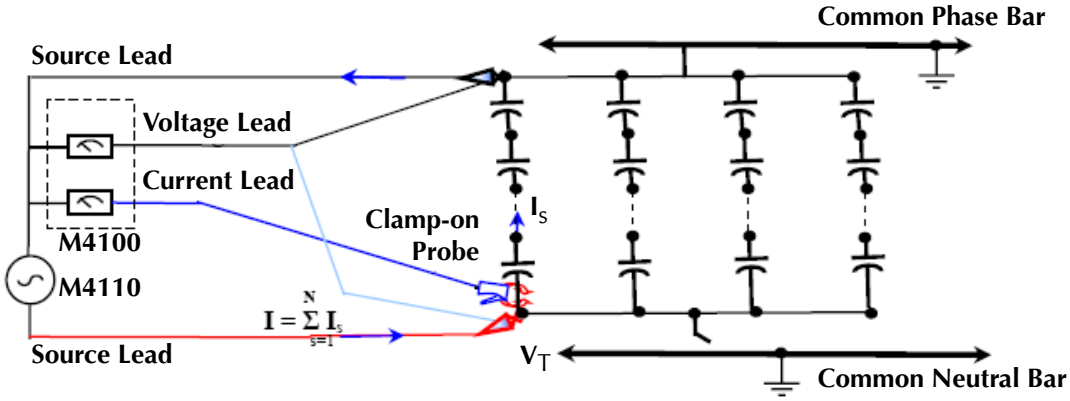


Figure 8. Test Principle for an Entire Serial String

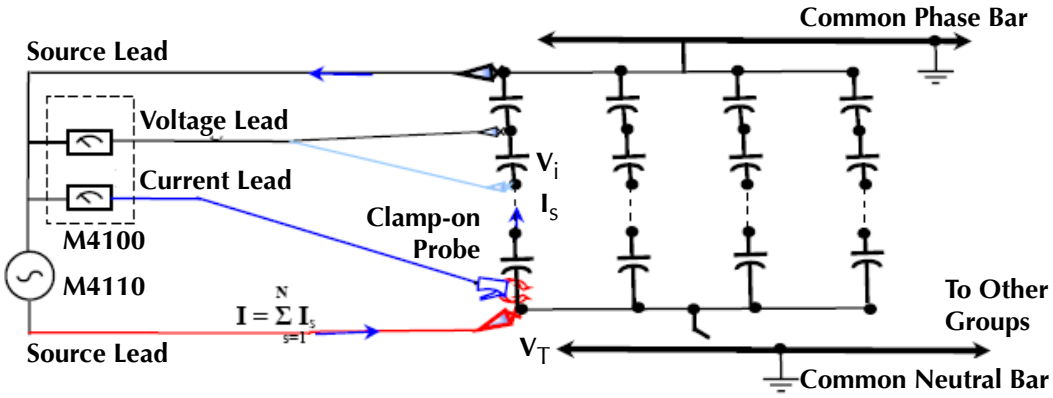


Figure 9. Test Principle for a Unit in a Serial String

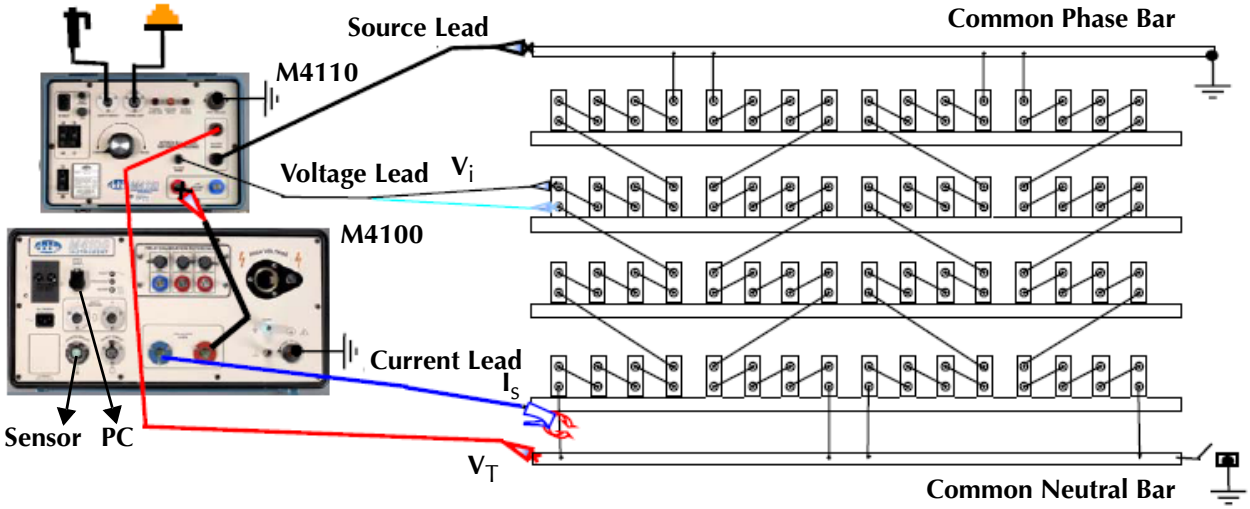


Figure 10. Test Connection for a Unit in a Serial String

Table 1 summarizes the test procedures.

Table 1. Capacitor Bank Test Procedures Using the M4110

	M4110 Connections			M4100 Connections			Test Description
Test	**Voltage Sense Lead**	**Red Lead**	**Black Lead**	**Mode**	**Red LV Lead**	**Blue LV Lead – Current Probe**	
1	Black to Black Lead White to Red Lead	Cap. Group Top	Cap. Group Bottom	UST-B	M4110 Red Terminal	Cap. Unit Bushing	Fig.1B and 4
	Repeat Test 1 on each unit in the group by moving only the current probe. Repeat the process for each parallel group in the capacitor bank. The current probe polarity must agree with the current circulation or source polarity. If the M4110 main breaker trips when the safety switch is depressed, remove the ground on the capacitor bank neutral.						
2	Across the capacitor unit	Cap. String Bottom	Cap. String Top	UST-B	M4110 Red Terminal	Cap. Unit Bushing	Fig. 2C
	Repeat Test 2 on each unit in the string by moving only the Voltage Sense lead. Repeat the process for each parallel string in the capacitor bank. The current probe and VS lead polarity must agree with the current circulation or source polarity. The black VS leads are across the capacitor unit under test, with the black lead closer to the black source lead and the white lead closer to the red source lead.						

Using the External Reference Screen

M4000 software is necessary for these tests. This software has an External Reference screen (Figure 11) similar to the Clipboard screen. Use the following settings:

- **External Cap./Res.** provides a choice of two coupling devices: capacitor (pF) or resistor (ohms). Select Ohms, with 72000 as the default value, when using the M4110. The pF option is only for using an external coupling capacitor.
- **Cap./Res. %PF Value** allows you to enter a correction factor for coupling capacitor loss. Use the direct-measured % PF when using a coupling capacitor, and leave the field blank when using the M4110.
- **Max. Voltage** should be ≤ 0.6kV.
- **Current Atten.** is the (attenuation or ratio of the current probe. Use 1000 in this column for the Doble current probe.
- **Corr. Fctr.** is the correction factor for the measured power factor. Use -1 in this column for the Doble current probe.

The information in the first four items above is essential for the measurement; these fields must be properly filled out before beginning to test. It is also a good idea to include as much nameplate and Test Condition information as possible, for future reference and test data analysis. You can enter additional information in the Sheet Note at the bottom of the screen.

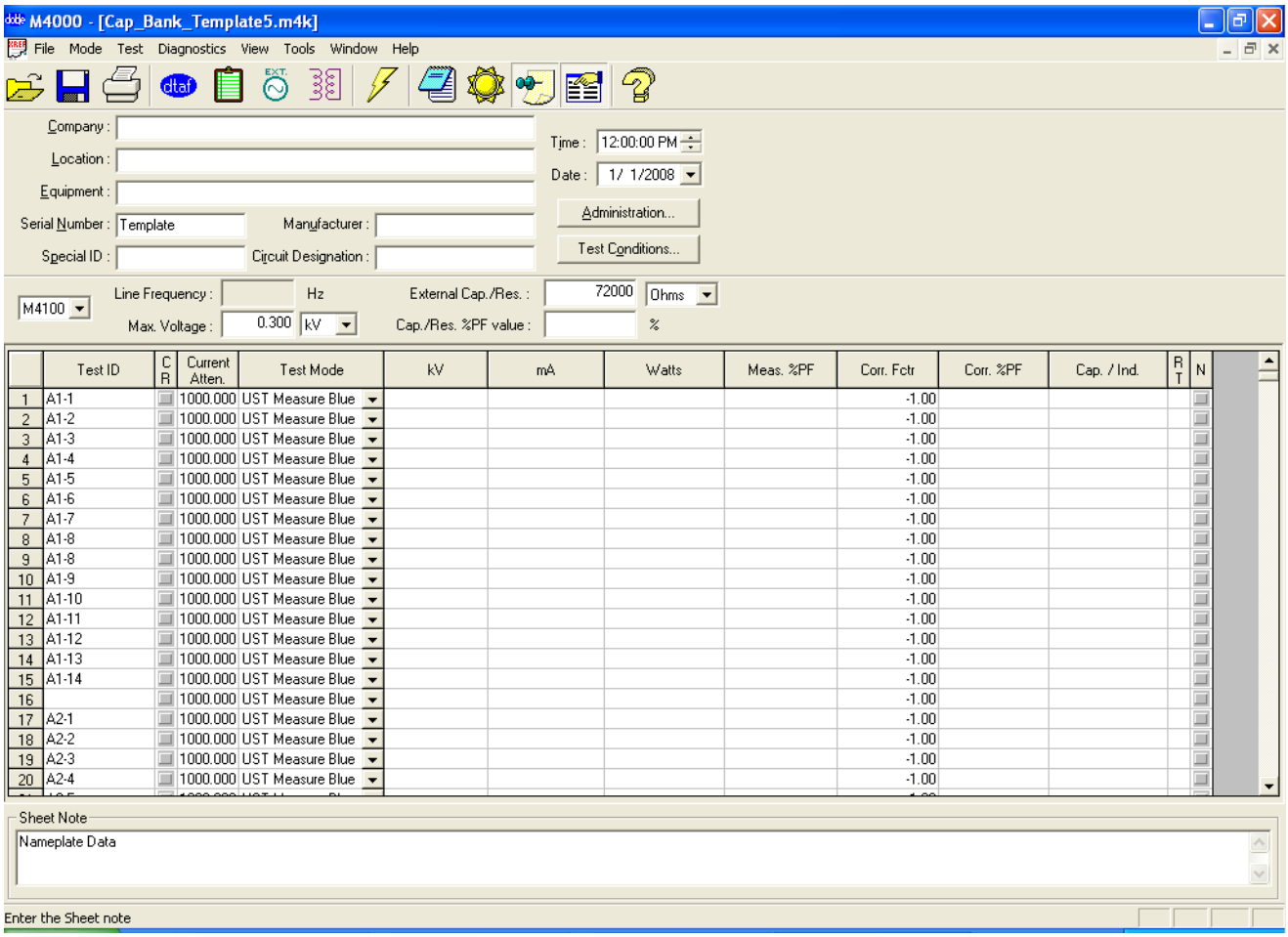


Figure 11. Test Plan Template

Creating a Test Plan

It is advisable to create a test plan before going to the field, using nameplate information and a drawing of the capacitor unit and bank.

Two test-plan templates are provided: CapBank_Template2.m4k and CapBank_Template5.m4k, for capacitor banks with two and five racks per phase, respectively, and fourteen capacitors in each rack.

You can modify these templates for other capacitor banks with different arrangements. To add a test line, press Ctrl + Ins or select Tools > Insert A Test Line. To delete a test line, press Ctrl + Del or select Tools > Remove An Empty Test Line.

Other test templates are available on request by contacting a Doble Client Service engineer.

Running a Test

1. Place the cursor on the desired starting test line.
2. Press F2, click the Single Test (lightning bolt) icon, or select Test > Run The Tests.

   The External Reference Test dialog box appears (Figure 12).

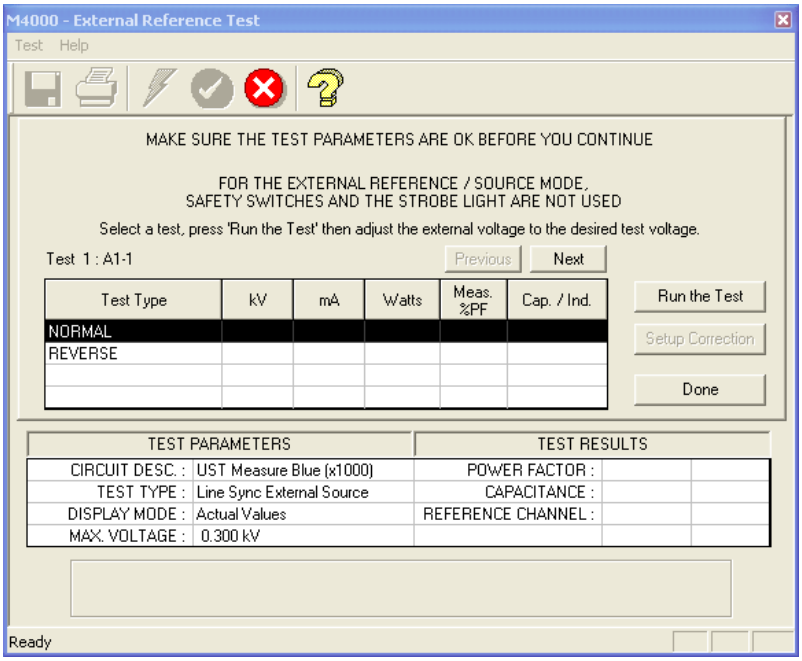


Figure 12. External Reference Test Dialog Box

   Only the NORMAL test needs to be performed.

3. Click Run The Test.

   The first time you run a test, a message appears (Figure 13), indicating that the instrument is measuring and recording the line frequency.

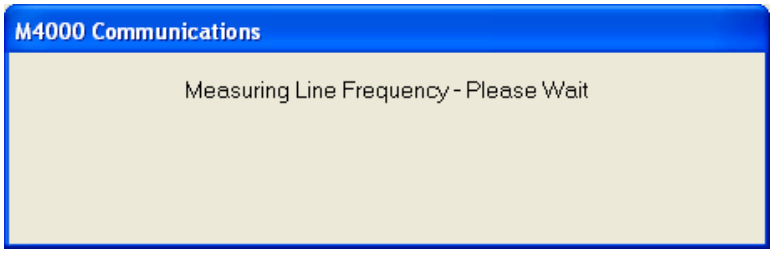


Figure 13. M4000 Communications Dialog Box

4. The Test-In-Progress dialog box appears (Figure 14), with the message SET TEST VOLTAGE for LINE (x), where (x) is the selected line number.

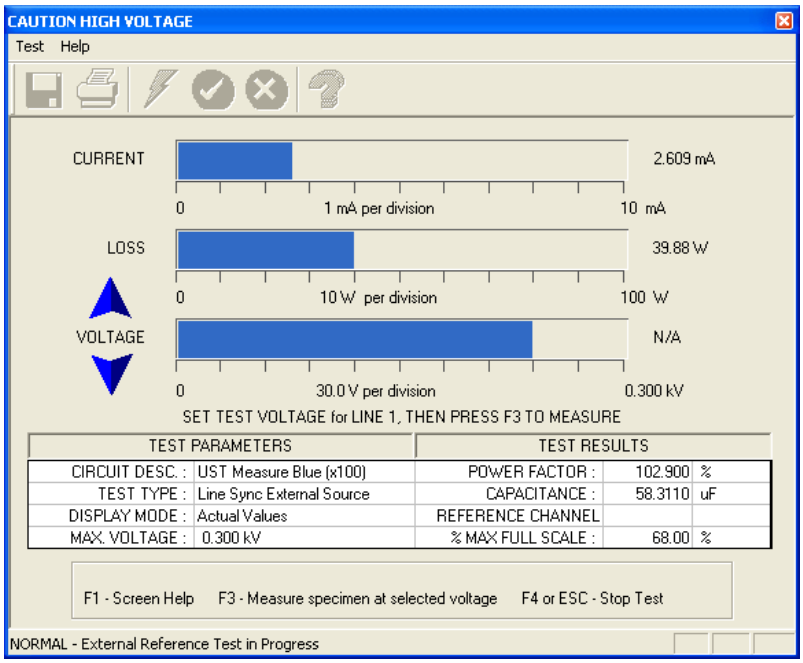


Figure 14. Test-in-Progress Dialog Box

5. If this is the first test in the capacitor group, use the M4110 voltage knob to adjust the test voltage to the desired level (240 V), displayed in the voltage ramping bar.

   If this is a subsequent test in the group, go to step 6.

6. When you are ready to take the measurement, press F3.

   The message DO NOT CHANGE VOLTAGE – COLLECTING DATA appears.

7. When the message TEST DONE, LINE (x) appears, press one of the function keys indicated at the bottom of the screen to continue. These options are also available from the toolbar and menus.

   - **F1.** Opens the Help window.
   - **F2/F11.** F2 restarts a single test; F11 restarts a multiple test.
   - **F5.** Accepts the results of the test. When performing multiple tests, only those completed before a stopped test are accepted.
   - **F6.** Discards the results.
   - **F7.** Prints the results.
   - **F8.** Saves the results.

NOTE

Capacitance in the Test Results column of Figure 12 or Figure 14 becomes Inductance when the current probe or Voltage Sense lead polarity does not agree with the source polarity. Reverse the current probe or VS lead to correct the polarity. Abnormally low capacitance can also be caused by current-probe jaws that are not fully closed.

8. Click Next to test the next unit.
9. Repeat steps 3 through 8 until the end of the group.
10. Click Done.
11. Return the M4110 voltage knob to the zero position.

    To test another group or rack, change the test connection and repeat the above procedure. The M4110 voltage knob must be reset to zero to initiate another test. See [2] and [3] for more detailed instructions on M4110 operation.

Test Voltage

The test voltage should not exceed 600 V, due to the rated voltage of the leads and current probe. The total test current is limited to the rated current of the test source.

In general, the total test current (*I*) is a function of the test voltage (*V*), frequency (*f*), and total capacitance (*C*) of the capacitor group under test. Equations 1 and 2 permit calculating the test current and capacitance of the group under test.

$$I = 2\pi fCV \qquad (1)$$

where:

I = total test current

f = test frequency

C = total capacitance

V = test voltage

and

$$C = \sum_{i=1}^{N} C_i \qquad (2)$$

where:

N = the unit number in the capacitor group

C_i = the capacitance of the unit capacitor

For a 60 Hz system, the preferred test voltage is 240 V. If the total capacitance of the capacitor group under test is too large, causing the protective devices to operate, reduce the test voltage to 120 V. For a 50 Hz system, you can use Equation 1 and the above general guideline. Table 2 shows the summary.

Table 2. Recommended Test Voltage for Capacitor Banks

60 Hz System		50 Hz System	
Test Voltage (V)	**Total Group Capacitance (µF)**	**Test Voltage (V)**	**Total Group Capacitance (µF)**
240	< 221	= 600	< 3183 * I / V
120	≥ 221		
If the test current still exceeds the rated current of the source due to the size of the capacitance of the group capacitor, the test voltage can be reduced.			

Test Data Interpretation

- **Power Factor.** The power-factor test is the most effective known field test procedure for the early detection of contamination, tracking, partial discharge, and deterioration.
- **Capacitance.** Short-circuited condenser layers or sections of capacitor result in increased capacitance and charging current. Conversely, a decreased capacitance and charging current indicate condenser layer discontinuity, or delamination due to missing fluid. A capacitance change is a good indication of internal damage or deformation.

In general, capacitance should be within ±5% of the nameplate value, and power factor should be 3% or less. These limits should be used in conjunction with historical data analysis, comparison with test results on similar units, and the manufacturer's recommendations. Always consider test conditions in any comparison study, since the capacitance and % PF can vary with temperature and humidity.

The External Reference software requires manually reviewing the test data. The author recommends performing this analysis task graphically in a spreadsheet program (Excel), by exporting the data electronically.

References

[1] Long Pong, "Field Testing Capacitor Banks with M4000 Test Instrument," *Minutes of the 73nd Annual International Conference of Doble Clients, 2006*, in Arresters, Capacitors, Cables and Accessories Committee paper ACCA 7.

[2] Doble Engineering Company, *M4000 Insulation Analyzer User Guide,* PN 500-0110.

[3] Doble Engineering Company, *M4110 Leakage Reactance Interface User Guide,* PN 500-0396.

[4] Long Pong, "Update – Field Testing Capacitor Bank with M4000 Test Instrument," *Minutes of the 74th Annual International Conference of Doble Clients, 2007*, in Arresters, Capacitors, Cables and Accessories Committee paper ACCA 3.