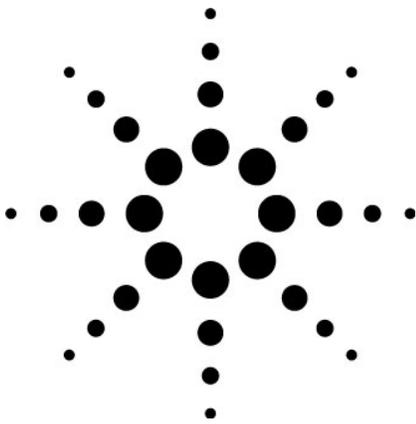


# Evaluation of High Power Devices Using External DC Power Supply



## Application Note E5270-6

- Maximum 500 W Output
  - 50 A/8 V (Agilent 6651A)
  - 25 A/20 V (Agilent 6652A)
  - 10 A/50 V (Agilent 6654A-J05)
- Fast measurement speed
- Accurate

## Agilent E5270 Series of Parametric Measurement Solutions



Agilent E5270A 8 Slot Parametric measurement Mainframe with 4 SMU plug-in modules



Figure 1. Agilent 665xA series Performance DC Power Supply

### Introduction

High power devices up to 500 W can be measured precisely with the Agilent E5270A Parametric Measurement instrument by combining it with the Agilent 654X/664X/655X/665X series performance DC Power Supply (Figure 1).

One of the emerging areas of developments in high power device is lowering the on resistance that is used for controlling the motors, actuators and inverters. The low on resistance improves the energy efficiency of electric cars, air conditioners or power inverters used to convert, for example, from solar energy to home AC line voltage. Some of these technologies are already used or expected to be widely used in the near future. So the low on



resistance of the power device is very important both for reducing energy consumption and for building or fabricating these function blocks more simply. This combination, of course, can be used in general applications where 1 A HPSMU cannot be covered.

The possible expansions of the power measurement ranges are shown in Figure 2, and the combination provides the accuracy, power and measurement speed required in these applications.

High current measurements are possible with the traditional curve tracer, but it does not provide the accuracy and freedom of measurements required in DC characterization.

This application note describes how to configure these power supplies with the Agilent E5270A and the know-how that is required in high power measurements.

One of the features of the E5270 series instruments is the high measurement speed; combining this feature with the external power supply satisfies the requirements needed in precise characterization in high power devices.

The measurements can be made while controlling the measurements interactively using the Agilent I/CV software or automatically from the user written program.

The Agilent I/CV software provides not only the interactive measurements setup and measurements capability, but also

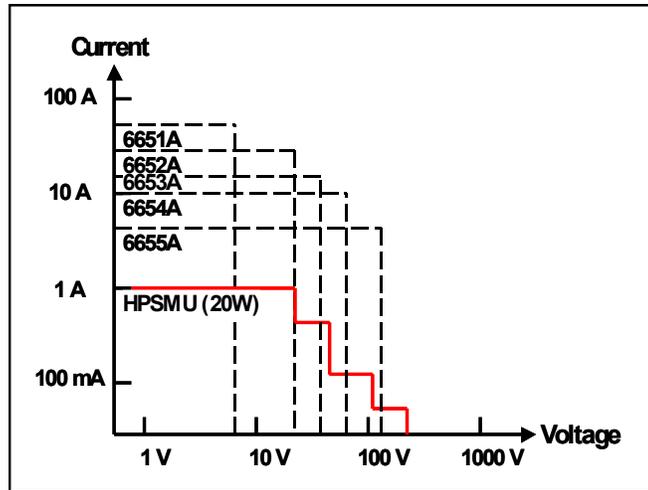


Figure 2. Expanding the output power

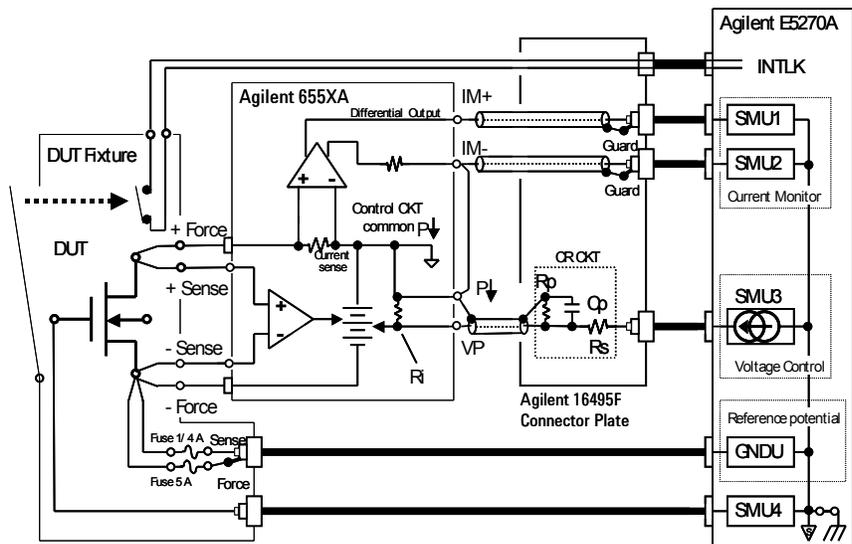


Figure 3. Connection Block Diagram (1) - for accuracy,

provides an automatic analysis capability such as  $V_{th}$  extraction. The I/CV provides a simple programming capability for creating the measurements sequence for improving the measurement efficiency. For production use, a user written program is effective for achieving the highest measurement speed.

## Key Techniques for Configuration

### Connection

Figure 3 shows the connection diagram of the Agilent E5270A, the Agilent power supply and the device under test (DUT) for positive voltage output.

SMU3 is connected to the modulation analog control terminal "VP" through the CR circuit to control the output voltage of the power supply. To

obtain maximum performance and stability, SMU3 is used in current force mode; this current is converted to a pseudo-floating voltage through the CR circuit, and this drives the power supply. SMU1 and SMU2 are connected to the current monitor output IM+ and IM- of the power supply; the difference of the two SMU readings is converted to the current flown from the power supply.

The power supply output is connected to the DUT using the Kelvin connection; the GNDU provides the measurements common level to the power supply by connecting to the Kelvin sense point at the DUT contact.

Since the maximum current of the power supply can exceed ten amperes, fuses are inserted between the -Force terminal of the power supply and the GNDU to protect the GNDU from any possible damage. If the positive output of the power supply is accidentally shorted to the circuit common or the chassis of the E5270A, then the maximum current output of the power supply, that is more than the 4 A limit of the GNDU, flows into the GNDU and may damage the GNDU. The fuses are used to protect the GNDU.

These connections are made using the Agilent 16495F-002 connector plate. (Figure 4) The CR circuit and shielded cables can be soldered to the unused connector terminal of the 16495F to firmly secure the CR component. (Figures 5a and 5b)

Figure 6 is another example of a connecting diagram that can be used when the current flowing from SMU4 (or other SMUs if additional connections are made) is small and the voltage drop in the GNDU wiring by the return current to the GNDU is negligible compared to the required accuracy.

Figure 7 is the connection diagram for negative voltage output to the DUT. If the current flowing from/in the GNDU is large and the voltage drop cannot be ignored, then the GNDU should be used for providing the Kelvin connection, as in the example of Figure 3.

Figure 8 shows a wiring example of the connection terminal in the back panel of the power supply. The CR circuit can be directly connected in the connection terminal instead of using the connector plate shown in the implementation example. In that case, the wiring must be secured to the plastic case or back panel of the power supply to ensure certain connection of the control signal between the E5270A.

### CR value

The CR value and the parameter conversion factor to control the power supply from the E5270A is provided.

Table 1 shows the parameter for positive output for each Agilent power supply model that can be used in this application.

Table 2 provides the parameters for negative output.

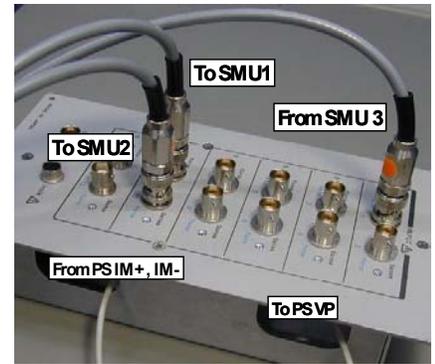


Figure 4. CR Circuit Implementation (Example using connector plate)

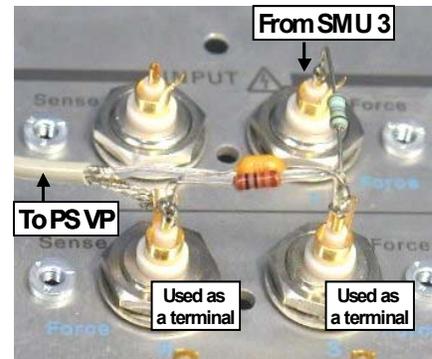


Figure 5a. CR circuit wiring (SMU V control) using the connector plate

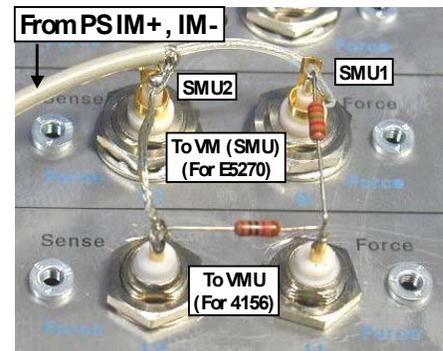


Figure 5b. CR circuit wiring I Monitor) using the connector plate

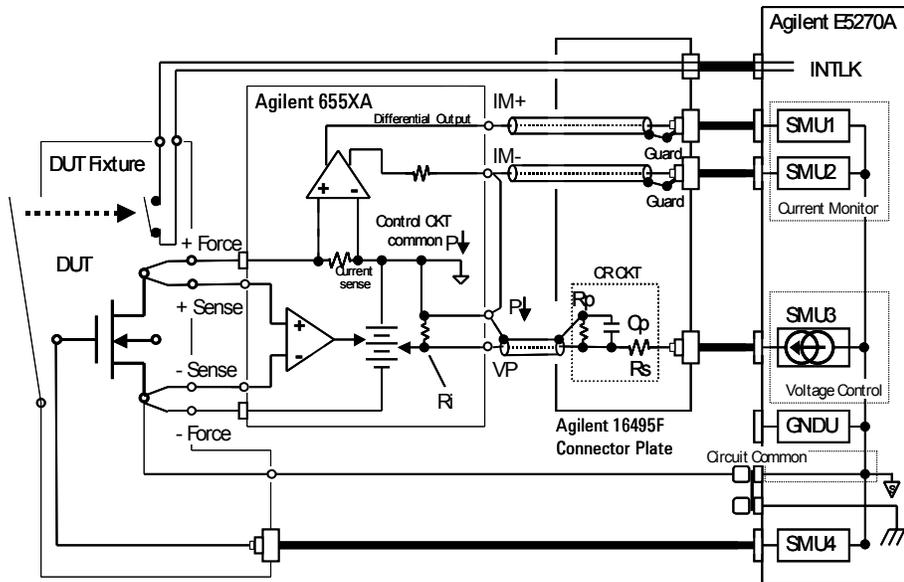


Figure 6. Connection Block Diagram (2) - for safety, +Vo

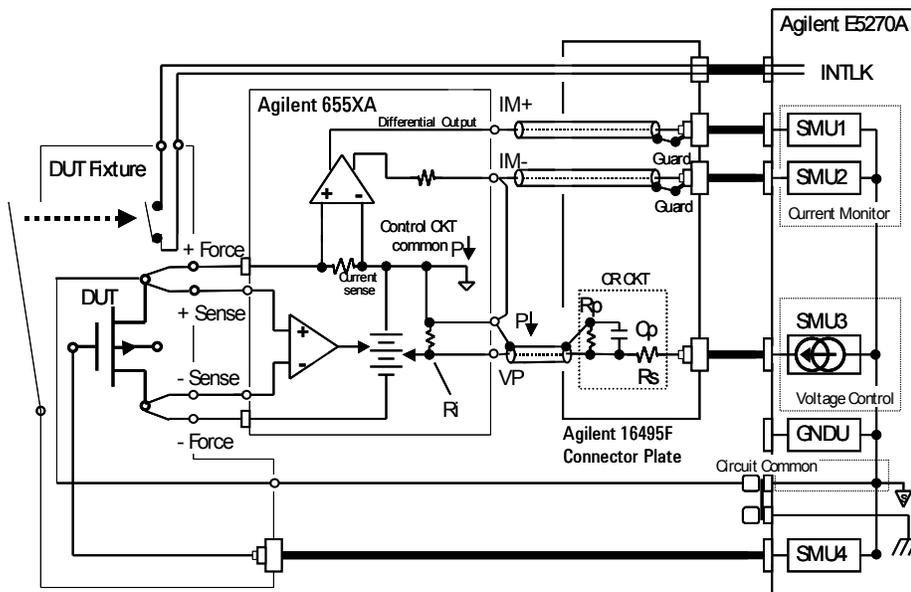


Figure 7. Connection Block Diagram (3) - for safety, -Vo



Figure 8. Power supply terminal connection

Agilent Power Supply Model	F.s. Voltage	F.s. Current	R <sub>p</sub>	R <sub>s</sub>	I Force (SMU) / P.S.V Output	V Force (SMU) / P.S.V Output	P.S.I Output (A) / P.S.I Monitor (V)
6641A/ 6541A	8	20	1000	2150	-0.0006875	-1.1031	-4.0000
6642A/ 6542A	20	10	1000	6810	-0.0002750	-1.1228	-2.0000
6643A/ 6543A	35	6	1000	12100	-0.0001571	-1.0443	-1.2000
6644A/ 6554A	60	3.5	1000	21500	-0.0000917	-1.0542	-0.7000
6645A/ 6545A	120	1.5	1000	46400	-0.0000458	-1.1683	-0.3000
6651A/ 6551A	8	50	1000	2150	-0.0006875	-1.1031	-10.0000
6652A/ 6552A	20	25	1000	6810	-0.0002750	-1.1228	-5.0000
6653A/ 6553A	35	15	1000	12100	-0.0001571	-1.0443	-3.0000
6554A/ 6654A-J05	50	10	1000	19600	-0.0001100	-1.2560	-2.0000
6654A/ 6554A	60	9	1000	21500	-0.0000917	-1.0542	-1.8000
6655A/ 6555A	120	4	1000	46400	-0.0000458	-1.1683	-0.8000

Note: Other parameters : R<sub>i</sub> = 10 kohm (Input R), C<sub>p</sub> = 0.1 uF

Table 1. CR CKT value (Positive output)

Agilent Power Supply Model	F.s. Voltage	F.s. Current	R <sub>p</sub>	R <sub>s</sub>	I Force (SMU) / P.S.V Output*	V Force (SMU) / P.S.V Output*	P.S.I Output (A) / P.S.I Monitor (V)
6641A/ 6541A	8	20	1000	2150	-0.0006875	-2.1031	4.0000
6642A/ 6542A	20	10	1000	6810	-0.0002750	-2.1228	2.0000
6643A/ 6543A	35	6	1000	12100	-0.0001571	-2.0443	1.2000
6644A/ 6554A	60	3.5	1000	21500	-0.0000917	-2.0542	0.7000
6645A/ 6545A	120	1.5	1000	46400	-0.0000458	-2.1683	0.3000
6651A/ 6551A	8	50	1000	2150	-0.0006875	-2.1031	10.0000
6652A/ 6552A	20	25	1000	6810	-0.0002750	-2.1228	5.0000
6653A/ 6553A	35	15	1000	12100	-0.0001571	-2.0443	3.0000
6554A/ 6654A-J05	50	10	1000	19600	-0.0001100	-2.2560	2.0000
6654A/ 6554A	60	9	1000	21500	-0.0000917	-2.0542	1.8000
6655A/ 6555A	120	4	1000	46400	-0.0000458	-2.1683	0.8000

\*The control signal polarity of the SMU to control the power supply is the same as the case for positive output. The polarity of the power supply output is referenced to the negative output terminal.

Table 2. CR CKT value (Negative output)

Note that the force current polarity of the SMU to set the power supply remains the same direction (always negative), but the actual voltage output polarity from the power supply is changed by the connection to the DUT. The compensation factor for current reading for negative voltage output is reversed to align the polarity of the SMU current reading.

Detailed technical information on these parameters and the theory of operation are provided in the technical note 5989-0920EN. Please refer to this publication to understand more about the stable control of the power supply and the measurement accuracy. More information about the publication is provided in the notes 2 at the end of this note.

**Measurement parameter conversion**

This technique controls the output voltage of the DC power supply using the analog signal from the SMU, and reads back the output current from the power supply as an analog voltage that is normalized to the maximum output current of the power supply; hence the parameters for these analog signals have to be converted properly.

1. Setting output voltage  
When you set the output voltage of the power supply, -5 V at the VP input of the power supply corresponds to the maximum output voltage rating of the power supply; 0 V at VP is for 0 V output from the power supply. For correctly controlling the power

supply from the SMU, the CR circuit is added and current source mode of the SMU is used. The current value that outputs 1 V from the power supply using the CR value in Table 1 is provided in the column "I Force (SMU) / P.S V output" as the V conversion factor. If Vo volts are output from the power supply, then the SMU is set to force current as Vo times the V conversion factor chosen from the appropriate power supply. This V conversion factor should be tuned or calibrated so that the set value and the actual output from the power supply match precisely.

2. Setting voltage compliance  
When the SMU drives the power supply in current force mode, the SMU must swing to an appropriate voltage that is determined by the CR circuit and the output voltage of the power supply. The voltage compliance of the SMU must be set larger than this voltage. This voltage can be determined by using the factor shown in the "V Force (SMU) / P.S V output" column, the ratio of the minimum required SMU force voltage and your power supply output voltage, Vo. Set the SMU voltage compliance larger than the Vo x "V Force (SMU) / P.S V output" value.

3. Current monitor  
The current monitor voltage from the power supply is normalized to -5 V for its rated maximum output current. Therefore the output current from the power supply can be converted using the current monitor output voltage by multiplying the current conversion factor (= "maximum current rating

of the power supply/(-5V)"). This factor is shown in the column "P.S I output (A) / P.S I monitor (V)".

Here are two examples of parameter conversion, one for positive output and the other for negative output, for interfacing to the power supply.

Example 1. Positive V:

- Power supply : 6654A-J05 (10 A/50 V)
- Output voltage setting : 10 V (positive V connection)

1. The I force current of SMU3 to output 10 V:

From Table 1, "I Force (SMU) / P.S V Output" = -0.000110 (A/V)

$$I \text{ force} = -0.000110 \text{ (A/V)} \times 10 \text{ (V)} = -0.0011 \text{ A}$$

2. V compliance of SMU3:  
From Table 1, "V Force (SMU) / P.S V Output" = -1.256  
V compliance > 10 (V) x -1.256 = -12.56V.

Considering a margin to cover the voltage drop of the force line of the power supply and the error of the CR circuit, a value greater than -15 V is advisable.

3. Current monitor conversion:  
From Table 1, "P.S I Output (A) / P.S I Monitor (V)" = -2.00

For example, if the voltage reading of "+IM - -IM" is -2.5 V, then the actual current output from the 6654A-J05 is 5 A (= -2.5 V x -2.0 A/V).

4. Current monitor SMU parameters (SMU1, SMU2)  
 Since these SMUs are used as voltage monitor, the basic setting of the SMU is I force/V monitor mode.  
 V compliance: The same as the maximum voltage of the power supply : 50V  
 I compliance: 1 uA  
 (considering the slew rate of the SMU)

Example 2. Negative V:

- Power supply : 6652A (25 A/20 V)
- Output voltage setting : -10 V (negative V connection)

1. The I force current of SMU3 to program P.S V output 10 V:  
 From Table 2, "I Force (SMU) / P.S V Output" = -0.0002750 (A/V)  
 $I \text{ force} = -0.000275 \text{ (A/V)} \times 10 \text{ (V)} = -0.00275 \text{ A}$
2. V compliance of SMU3:  
 From Table 2, "V Force (SMU) / P.S V Output" = -2.1228  
 $V \text{ compliance} > 10 \text{ (V)} \times -2.1228 = -21.228\text{V}.$   
 Considering a margin to cover the voltage drop of the force line of the power supply and the error of the CR circuit, a value greater than -25 V is advisable.
3. Current monitor conversion:  
 From Table 2, "P.S I Output (A) / P.S I Monitor (V)" = 5.00  
 For example, if the voltage reading of "+IM - -IM" is -2.5 V, then the actual current output from the negative output terminal of 6652A is -12.5 A (= -2.5 V x 5.0 A/V).

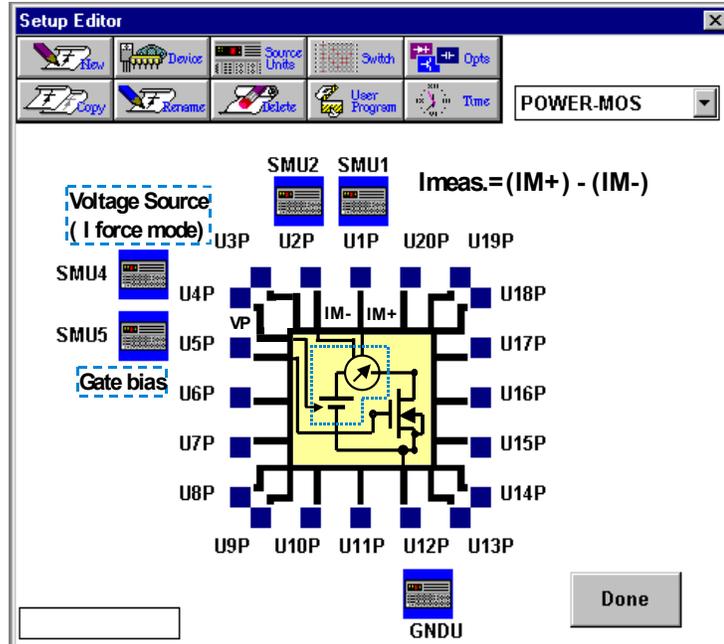


Figure 9. I/CV connection setup

4. Current monitor SMU parameters (SMU1, SMU2)  
 Since these SMUs are used as voltage monitor, the basic setting of the SMU is I force/V monitor mode.  
 V compliance (the voltage is in the SMU circuit common level) : 10 V  
 I compliance : 1 uA

### Results using Agilent E5270A and Agilent 6654A-J05

The measurements can be performed in two ways. One is interactive measurement using the Agilent I/CV software and the other is by user written program.

### Using Agilent I/CV

The I/CV setup screens for the drain characteristics measurements are shown from Figure 9. On the Setup Editor

window (Figure 9), SMU1 and SMU2 are used as a differential volt-meter, and the voltage is converted to the current output from the power supply. SMU4 is used to control the output voltage of the power supply; a negative current is forced to the analog input terminal of the power supply through the CR circuit which converts the current to pseudo-floating voltage at the circuit common of the power supply. SMU5 is connected to the gate.

The I/CV Setup Editor does not have a device model that fits correctly the SMU, power supply and the DUT connection, so "USER model (IC)" is used.

The circuit connection illustrated in the IC in Figure 9 is drawn for explanatory purposes and does not appear like this in the actual I/CV setup editor.

SMU1 Settings			SMU2 Settings				
Group	Parameter	Value	Group	Parameter	Value		
Info	SMU Type	MPSMU	Info	SMU Type	MPSMU		
	Pin ID	U1P		Info	Pin ID	U2P	
Measure	Meas. Voltage	<input checked="" type="checkbox"/> IMA	Measure		Meas. Voltage	<input checked="" type="checkbox"/> IMB	
	Meas. Current	<input type="checkbox"/> IU1P		Measure	Meas. Current	<input type="checkbox"/> IU2P	
	Meas. Time	<input type="checkbox"/> TMU1P			Measure	Meas. Time	<input type="checkbox"/> TMU2P
Bias	Stimulus	Current	Bias	Stimulus		Current	
	Bias Mode	Const		Bias	Bias Mode	Const	
	Bias Value(A)	1.0000E-05			Bias	Bias Value(A)	1.0000E-05
	Compliance(V)	20.0000				Bias	Compliance(V)

Figure 10. I/CV I-measure setup

Measurement Setup Dialog

Component	Summary
Mainframe	Mode Sweep
SMU1	Const Current 1.0000E-05
SMU2	Const Current 1.0000E-05
SMU4	Sweep Current 0.0000E-00
SMU5	Step Voltage 4.0000E-05
GNDU	Step Voltage 4.0000E-05

SMU4 Settings		
Group	Parameter	Value
Info	SMU Type	HPSMU
	Pin ID	U4P
Measure	Meas. Voltage	<input type="checkbox"/> VU4P
	Meas. Current	<input checked="" type="checkbox"/> IDC
	Meas. Time	<input type="checkbox"/> TMU4P
Bias	Stimulus	Current
	Bias Mode	Sweep
	Bias Sweep(A)	Sweep
	Compliance(V)	-20.0000
Meas. Range	Range Type	Fixed
	Range Limit(V)	40

SMU4 Sweep Settings		
Group	Parameter	Value
Bias Sweep	Type	Linear
	Stair	Single
	Start(A)	0.0000
	Stop(A)	-0.0011
	Step(A)	-2.2000E-05
	Points	51

Figure 11. I/CV Drain sweep setup

Measurement Setup Dialog

Component	Summary
Mainframe	Mode Sweep
SMU1	Const Current 1.0000E-05
SMU2	Const Current 1.0000E-05
SMU4	Sweep Current 0.0000E-00
SMU5	Step Voltage 4.0000E-05
GNDU	Step Voltage 4.0000E-05

SMU5 Settings		
Group	Parameter	Value
Info	SMU Type	MPSMU
	Pin ID	U5P
Measure	Meas. Voltage	<input checked="" type="checkbox"/> VP
	Meas. Current	<input type="checkbox"/> IU5P
	Meas. Time	<input type="checkbox"/> TMU5P
Bias	Stimulus	Voltage
	Bias Mode	Step
	Bias Sweep(V)	Setup
	Compliance(A)	0.1000
Meas. Range	Range Type	Auto
	Range Limit(A)	100m

SMU5 Sweep Settings		
Group	Parameter	Value
Bias Sweep	Type	Linear
	Start(V)	4.0000
	Stop(V)	5.5000
	Step(V)	0.3000
	Points	6

Figure 12. I/CV Gate step V setup

The parameters set for each SMU are shown in Figures 10 through 12.

The transform editor shown in Figure 13 includes the conversion equation of the SMU1 (IMA) and the SMU (IMB) to the current (IDPS) and the equation to convert the current value to the actual output voltage (VD) from the power supply. The drain sweep voltage VD is not a measured value, but a converted value from the current sweep value of SMU5 in the I/CV setting.

Figure 14 shows the graphic display setup and Figure 15 the measurement results of the I/CV using the above parameters.

### Using a user written program

If the application is for production use where many tests are made in a short time, or a special setup is required, then control by a user written program is an option.

Figure 16 shows an example of a Gummel plot of the power bipolar transistor measured using a PC program. Precise characterization in the high current region can be done easily.

Figures 17 through 19 show the effect of device drift caused by the self heating of the measurement I/V power. The measurement is made using a double sweep to the drain from zero to stop voltage, and then swept back from the stop voltage to zero volts. Since the DUT is heated heavily (12.5 V x 9 A = 112 W) by the measurement current at around the stop voltage of the initial sweep starting from zero volts, the device

characteristics sometimes differ when swept back from the peak drain voltage because the device temperature rises considerably.

The characteristics in Figure 17 are measured with a linear sweep (faster) of the E5270A with a 21-point step between 0 to 12.5 V of the drain. The measurement time for one sweep step is about 20 ms in the example, and a small hysteresis appears in the double sweep measurement curve in the last gate voltage step.

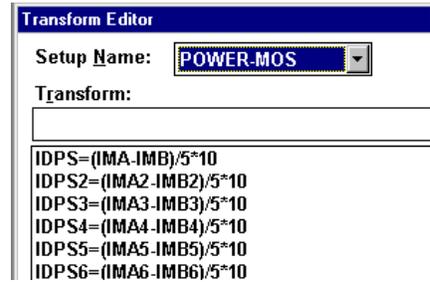


Figure 13. I/CV transform editor

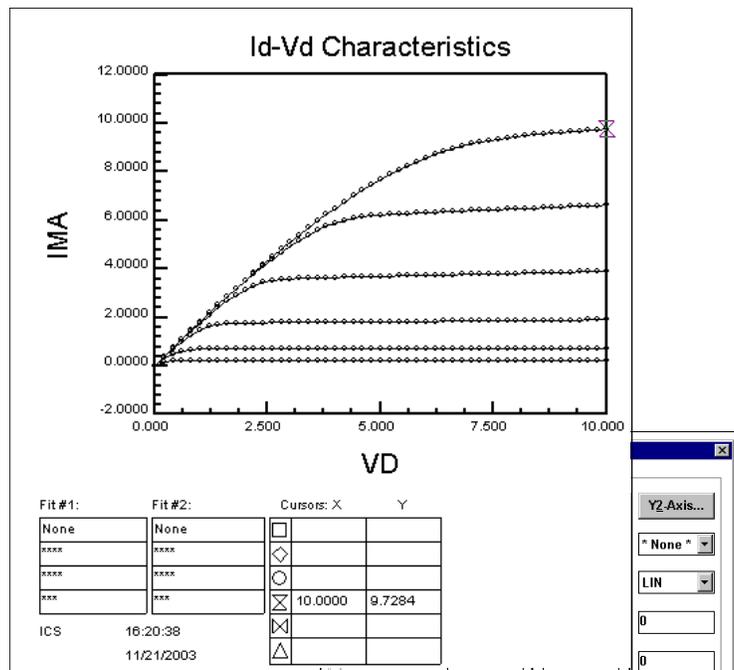


Figure 15. I/CV Measurements example

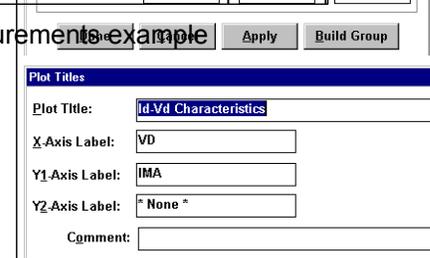


Figure 14. I/CV Plot setup

Figure 18 shows an experimental result measured using a longer (100 ms) sweep step time. It clearly shows a larger hysteresis in the measurements curve. The faster sweep is better for accurate characterization of the power device for reducing the self-heating effect.

Figure 19 shows a measurement result using a pulsed gate voltage to reduce the average power; there is no difference seen in the double sweep curve. The pulse is program-generated using a combination of voltage forth commands, and the generation of a narrower pulse is limited.

The Agilent E5270A has a built-in pulsed measurement capability which can generate a narrower (0.5 ms) pulse than programmed from the PC. If you add a simple differential amplifier for current measurements as shown in Figure 20, then you can use the built-in narrow pulsed sweep measurements of the E5270A for more precise characterization. Using the differential amplifier can eliminate the differential measurements with a two SMUs which block the pulsed measurements, thus making the built-in narrow pulsed measurements possible.

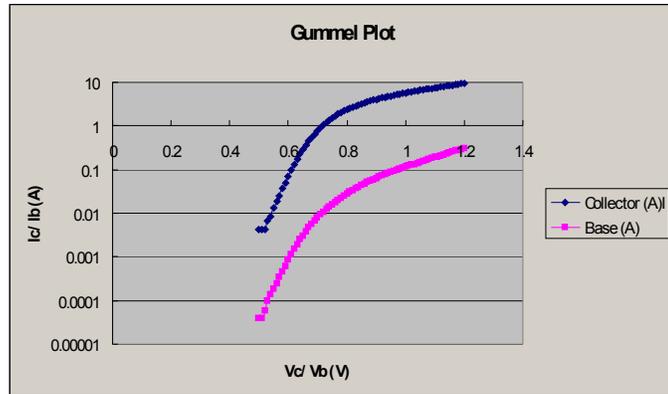


Figure 16. Gummel Plot example

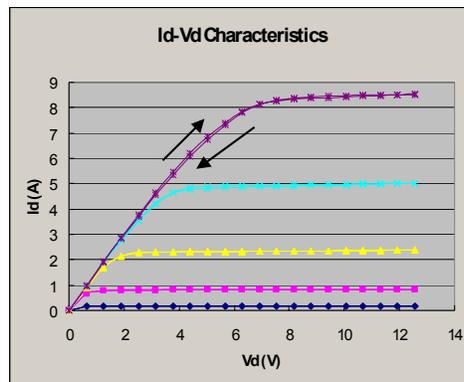


Figure 17. Double sweep with 10 ms step delay time

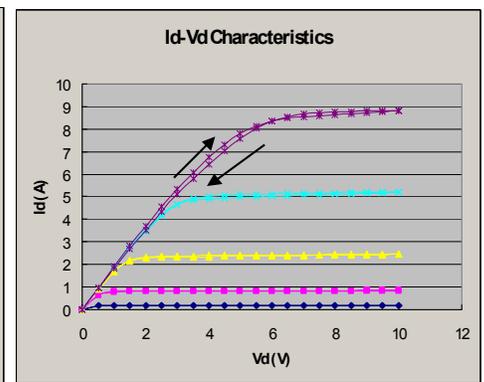


Figure 18. Double sweep with 100 ms step delay

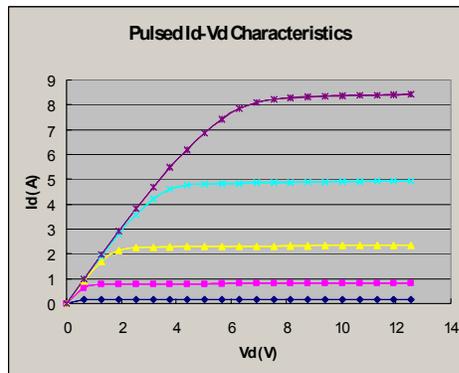


Figure 19. Pulsed Double sweep with 100 ms pulse period

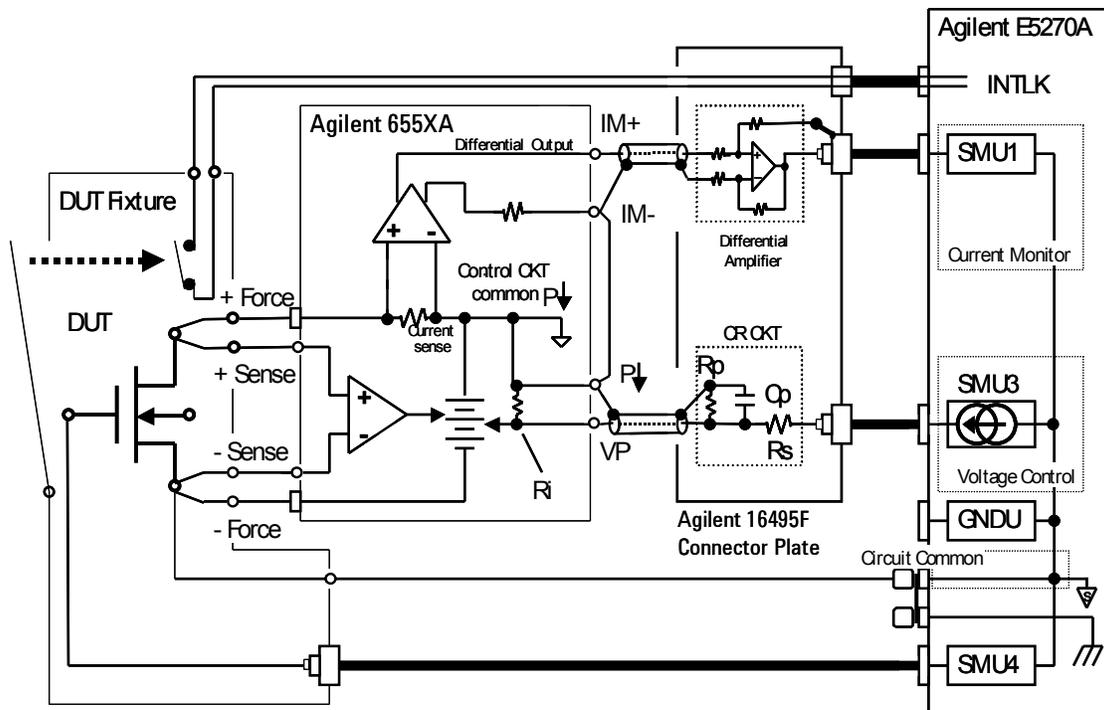


Figure 20. Connection Block Diagram (4) - for safety, Pulsed  $+V_o$

### Accuracy and Transient response

This combination can provide about 0.1 % voltage set accuracy and 0.2% current measurement accuracy.

The transient response of less than 1ms can be expected.

This performance is suitable for characterizing the newly developing power devices such as SiC technology.

Refer to technical note 5989-0920EN for more details.

### Conclusion

This application note describes how the Agilent E5270A can expand the output current used with the Agilent 654X/664X/655X/665X series performance DC Power Supply. You can expand the measurement current to as large as fifty amperes, for example, with the Agilent 6651A power supply. There are several choices for the Agilent power supply depending on your range of power requirements, and it can be implemented very easily.

The good accuracy in both voltage setting and current reading together with the fast transient response, suits characterizing newly developing devices and technologies such as SiC power transistors for automotive use, energy inverters

for solar cells in home use and any precision characterization of power devices.

### Notes:

1. Please observe the following safety precautions when using the Agilent E5270A and the Agilent external power supply.
  - Make sure that the wiring used has adequate current capacity.
  - To protect yourself against electrical shocks when replacing the DUT, be sure to fit an INTLK switch and install the DUT fixture in a shield box so you cannot touch the DUT while the measurement system is outputting voltage.
2. Refer to the Technical overview "Technique for

controlling Agilent External DC Power Supply from SMU to expand SMU output power capability", Agilent publication number 5989-0920EN to learn more about the stable control of the power supply and measurement accuracy. You can access this technical information and the I/CV sample setup file in the Agilent website.

3. IMPORTANT: FIRMWARE REQUIREMENT

The firmware version A01.05 or later is required to use the Agilent E5270A in this application.

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