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LEAKAGE CURRENT ESTIMATION IN POWER SUPPLY DESIGN

Theoretical Analysis of Leakage Current in a Medical Power Supply System

WHITEPAPER

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ABSTRACT

This paper provides a theoretical analysis method of leakage current in power supply systems. Medical power supply engineers should guide the design through theoretical analysis of leakage current of the system to ensure proper design margin, so that there is no risk of leakage current exceeding the standard requirement due to the error of Y capacitors in the mass production of medical power supplies. This helps to reduce production costs and improve quality while ensuring that all factory power supply products meet customer and safety leakage current requirements.

PROBLEM STATEMENT

In the design of medical power systems, multiple Y capacitors are generally used to solve Electromagnetic Interference (EMI) issues. The value of the leakage current of the power supply is verified, meeting the leakage current safety requirement or not, generally after the EMI is solved by choosing the Y capacitors by experimental methods. For power systems with multiple Y capacitors, designers often do not theoretically analyze the effect of each Y capacitor tolerance on the design margin of the power supply's leakage current; therefore, in mass production, the influence of the positive and negative errors of multiple Y capacitors on the leakage current can only be verified by batch production test to meet safety standards. There is no theoretical basis to prove whether the leakage current of the power supply in the design has a quality risk exceeding the safety requirements in production.

DESIGNERS OFTEN DO NOT THEORETICALLY ANALYZE THE EFFECT OF CAPACITOR TOLERANCE ON THE TOTAL DESIGN MARGIN OF THE POWER SUPPLY'S LEAKAGE CURRENT; THEREFORE, IN MASS PRODUCTION, THE INFLUENCE OF THE ERRORS OF MULTIPLE CAPACITORS ON THE LEAKAGE CURRENT CAN ONLY BE VERIFIED BY TESTING. IN OUR CASE STUDY, THE EQUIVALENT CIRCUIT OF THE PATIENT LEAKAGE CURRENT IS OBTAINED, AND THEN THE LEAKAGE CURRENT IS ESTIMATED BASED ON IT

In our case study, Phasium takes a medical power supply as an example, the equivalent circuit of the patient leakage current of the power supply is obtained, and then the leakage current is estimated based on it. The function between the positive and negative tolerances of the Y capacitor and the variation of the leakage current leakage current of the medical power supply is derived by using the total differential error analysis method. This has important theoretical guiding significance for the design of leakage current of medical power supply, the selection of Y capacitance accuracy and the evaluation of leakage current margin, as well as mass production testing and quality management.

BACKGROUND: The Equivalent Circuit for Patient Leakage Current Calculation and Formula Derivation

One medical power adaptor schematic which contributes the main patient leakage current is shown in Figure 1.

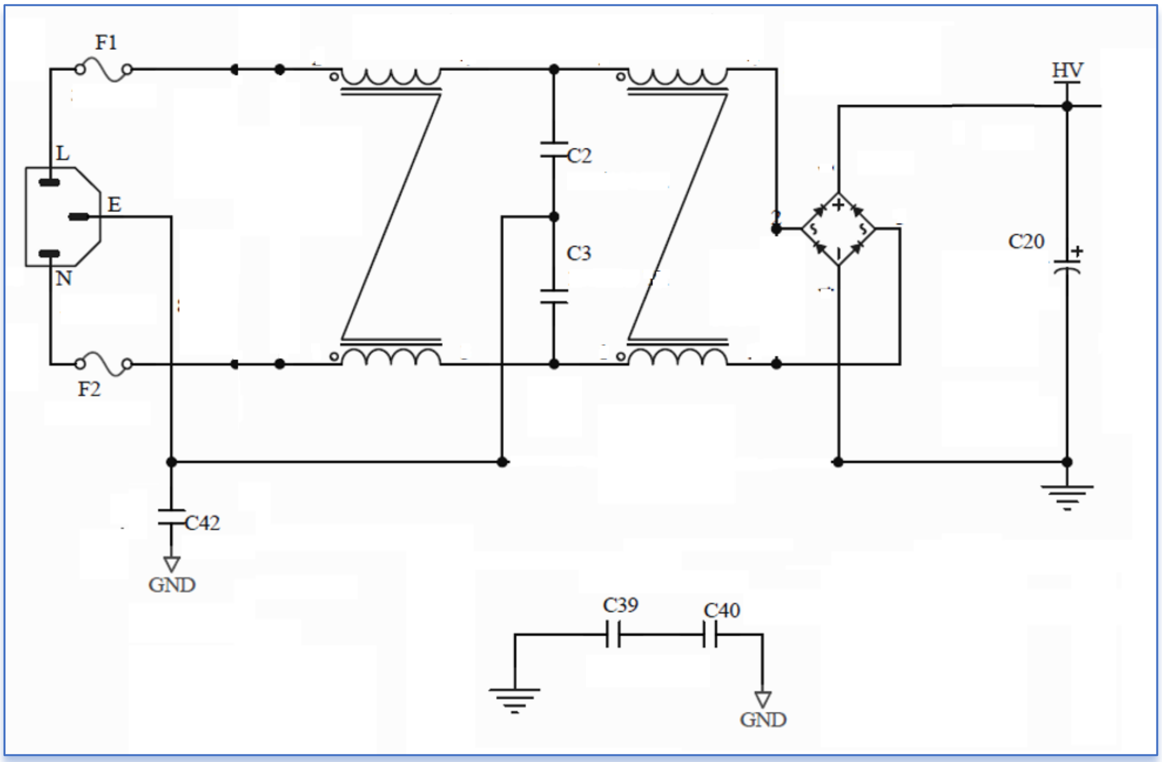


Figure 1: A Medical Power Supply Schematic

The PATIENT LEAKAGE CURRENT test in Figure 2 shows suitable test configuration for use in conjunction with the test PROCEDURES specified in IEC60601-1.

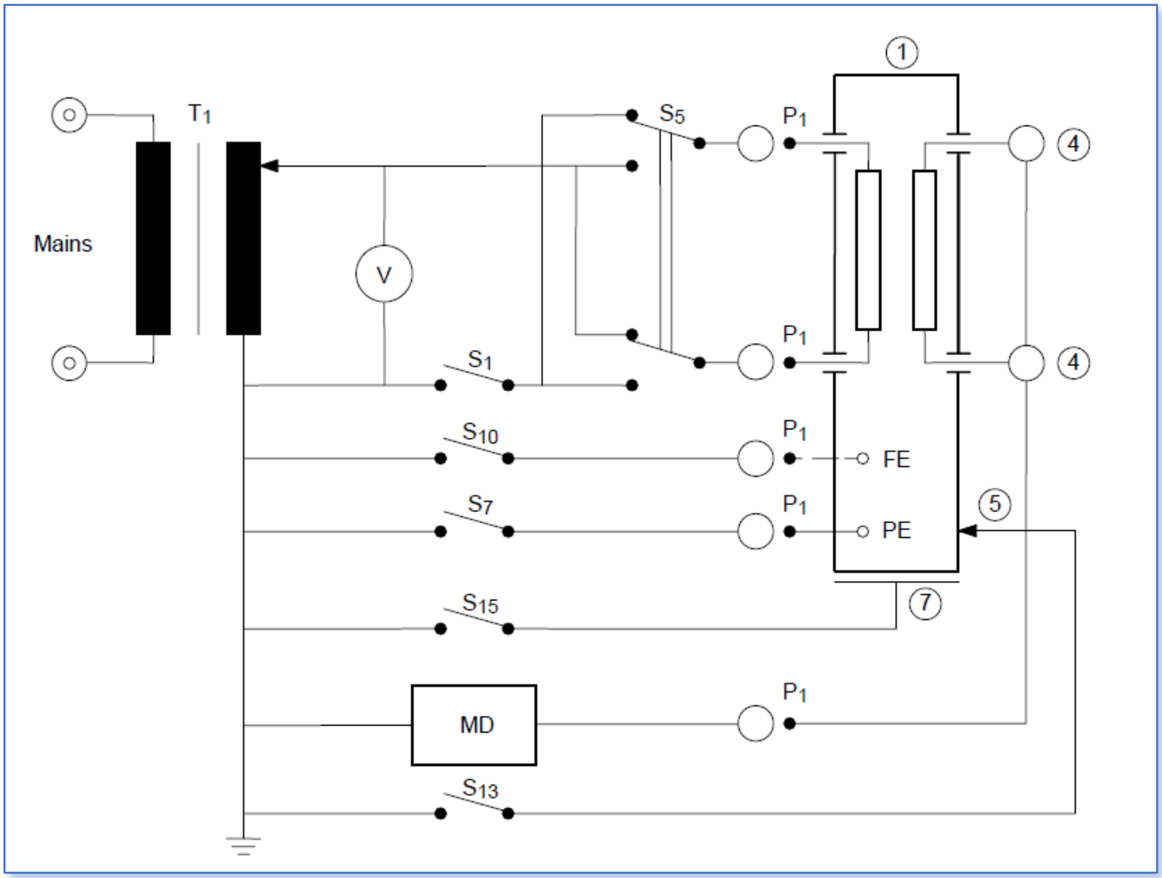


Figure 2: Measuring circuit for the PATIENT LEAKAGE CURRENT from the PATIENT CONNECTION to earth

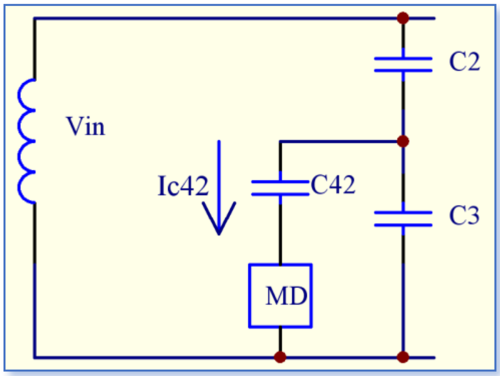


Figure 3: Equivalent Circuit for Patient Leakage Current IC42

From the above schematic and Patient Leakage Current measuring test setup, it is known that the Patient Leakage Current of the power adaptor is mainly the superposition of two currents IC42 and IC39 in the branches C42 and C39, respectively. The simplified equivalent circuit for Patient Leakage Current IC42 contribution is shown in Figure 3.

C42 is connected in parallel with C3, and then they are connected in series with C2. But only the current in C42 branch needs to be calculated for Patient Leakage Current contribution. According to Figure 3, the formula for I_{C42} calculation can be derived as follows:

$$\mathrm{I_{c42}} = \mathrm{Vin} * \omega * \frac{\mathrm{C_{42}} * \mathrm{C_2}}{\mathrm{C_{42}} + \mathrm{C_3} + \mathrm{C_2}} \qquad (1)$$

Where ω=2πf and f is the frequency of the voltage.

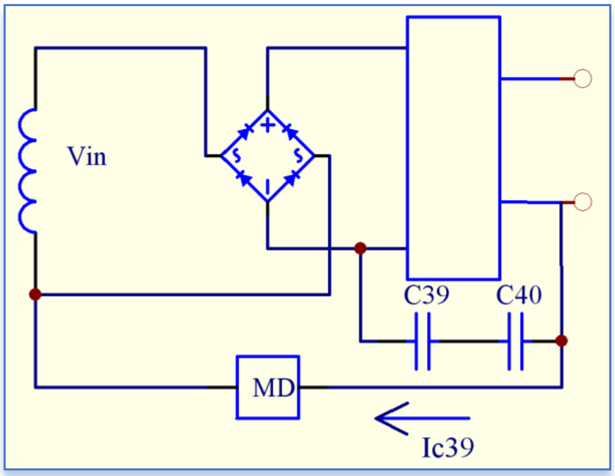


Figure 4: Equivalent Circuit for Patient Leakage Current IC39

The simplified equivalent circuit for Patient Leakage Current IC39 contribution is shown in Figure 4.

According to Figure 4, the branch I_{C39} consists of C39 and C40 in series. They are connected after the input rectifier bridge, so the voltage applied to C39 and C40 is the rectified half-wave sine voltage. Its Fourier Transformation is expressed as follows:

$$V_{halfwave} = \frac{V_{in}}{\pi} + \frac{V_{in}}{2}\sin(\omega t) - \frac{V_{in}}{\pi}\sum_{n=1}^{\infty}\frac{\cos(2n\omega t)}{4n^2-1} \qquad (2)$$

Omitting the DC component in the half-wave sine voltage in the Equation (2), its fundamental is the half of the sinusoidal input voltage. Thus, the formula for Patient Leakage Current I_{C39} at fundamental can be obtained as follows:

$$\mathrm{I_{c39}} = \frac{V_{in}}{2} * \omega * \frac{\mathrm{C_{39}} * \mathrm{C_{40}}}{\mathrm{C_{39}} + \mathrm{C_{40}}} \qquad (3)$$

The total Leakage current at fundamental is $I_{leakage1} = I_{C42} + I_{C39}$, that is,

$$I_{leakage1} = V_{in} * \omega * \{\frac{\mathrm{C_{42}} * \mathrm{C_2}}{\mathrm{C_{42}} + \mathrm{C_3} + \mathrm{C_2}} + \frac{1}{2} * \frac{\mathrm{C_{39}} * \mathrm{C_{40}}}{\mathrm{C_{39}} + \mathrm{C_{40}}}\} \qquad (4)$$

The contribution of third harmonic voltage generated by rectifier bridge side to the leakage current must be also considered. The third harmonic voltage has an amplitude of $\frac{V_{in}}{3\pi}$. The third harmonic leakage current can be estimated by the following formula:

$$I_{leakage3} = V_{in} * 3\omega * \frac{1}{3\pi} * \frac{\mathrm{C}_{39}*\mathrm{C}_{40}}{\mathrm{C}_{39}+\mathrm{C}_{40}} = V_{in} * \frac{\omega}{\pi} * \frac{\mathrm{C}_{39}*\mathrm{C}_{40}}{\mathrm{C}_{39}+\mathrm{C}_{40}} \qquad (5)$$

The total leakage current contributed by the fundamental and third harmonic can be calculated by

$$I_{leakage} = \sqrt{I_{leakage1}^2 + I_{leakage3}^2} \qquad (6)$$

The leakage current variation as a function of the tolerances of the Y capacitors can be derived as follows:

In Equation (4), the leakage current at fundamental has been expressed in variables of Y capacitances.

$$i_{leakage1} = i_1(\mathrm{c}_{42}, \mathrm{c}_3, \mathrm{c}_2, \mathrm{c}_{39}, \mathrm{c}_{40}) = \mathrm{Vin} * \omega * \{\frac{\mathrm{c}_{42}*\mathrm{c}_2}{\mathrm{c}_{42}+\mathrm{c}_3+\mathrm{c}_2} + \frac{1}{2} * \frac{\mathrm{c}_{39}*\mathrm{c}_{40}}{\mathrm{c}_{39}+\mathrm{c}_{40}}\} \quad (7)$$

The leakage current deviation of the power supply can be approximately expressed in the tolerances of the Y capacitors by using the definition of total differential on Equation (7).

$$\Delta i_{leakage1} \approx \frac{\partial i_1}{\partial c_{42}}\Delta c_{42} + \frac{\partial i_1}{\partial c_3}\Delta c_3 + \frac{\partial i_1}{\partial c_2}\Delta c_2 + \frac{\partial i_1}{\partial c_{39}}\Delta c_{39} + \frac{\partial i_1}{\partial c_{40}}\Delta c_{40}$$

$$= Vin * \omega * \{\frac{c_2*(c_3+c_2)}{(c_{42}+c_3+c_2)^2}\Delta c_{42} + \frac{-c_{42}*c_2}{(c_{42}+c_3+c_2)^2}\Delta c_3 + \frac{c_{42}*(c_{42}+c_3)}{(c_{42}+c_3+c_2)^2}\Delta c_2 + \frac{1}{2}\frac{{c_{40}}^2}{(c_{39}+c_{40})^2}\Delta c_{39} + \frac{1}{2}\frac{{c_{39}}^2}{(c_{39}+c_{40})^2}\Delta c_{40}\} \qquad (8)$$

The Equation (8) clearly shows the amount of change in leakage current caused by each Y capacitor error. It is noted that only the deviation in capacitance of the Y capacitor C3 can cause the leakage current to change in the opposite direction, that is, as the C3 capacitance increases, the leakage current decreases. All other deviations in the Y capacitances cause the leakage current to change in the same direction, that is, the capacitance increases and the leakage current also increases.

Equation (8) can also be used to find the contribution of the deviation of each capacitor to the leakage current.

We can use the same strategy to obtain the third harmonic leakage current variation as a function of the tolerances of the Y capacitors. In Equation (5), the third harmonic leakage current has been expressed in variables of Y capacitances.

$$i_{leakage3} = i_3(\mathrm{c}_{39}, \mathrm{c}_{40}) = V_{in} * \frac{\omega}{\pi} * \frac{\mathrm{C}_{39} * \mathrm{C}_{40}}{\mathrm{C}_{39} + \mathrm{C}_{40}}$$

The third harmonic leakage current deviation of the power supply can be approximately expressed in the tolerances of the Y capacitors by using the definition of total differential on Equation (9).

$$\Delta i_{leakage3} \approx \frac{\partial i_1}{\partial c_{39}} \Delta c_{39} + \frac{\partial i_1}{\partial c_{40}} \Delta c_{40}$$

$$= Vin * \frac{\omega}{\pi} * \{\frac{{c_{40}}^2}{(c_{39}+c_{40})^2} \Delta c_{39} + \frac{{c_{39}}^2}{(c_{39}+c_{40})^2} \Delta c_{40}\}$$

All the deviations in the Y capacitances C39 and C40 cause the leakage current to change in the same direction, that is, the capacitance increases and the leakage current also increases.

CASE STUDY: Medical Power Supply

The following is an example using the actual parameters of a medical power adaptor to analyze the influence of the tolerance of the Y capacitor on the leakage current of the power supply.

Given that $\mathrm{Vin} = 240\mathrm{Vac};\ \mathrm{f} = 50/60\mathrm{Hz}$,

$$\mathrm{C}_{42} = 2200\mathrm{pF}; \mathrm{C}_3 = 1000\mathrm{pF}; \mathrm{C}_2 = 1000\mathrm{pF};\ \mathrm{C}_{39} = 1000\mathrm{pF};\ \mathrm{C}_{40} = 1000\mathrm{pF};$$

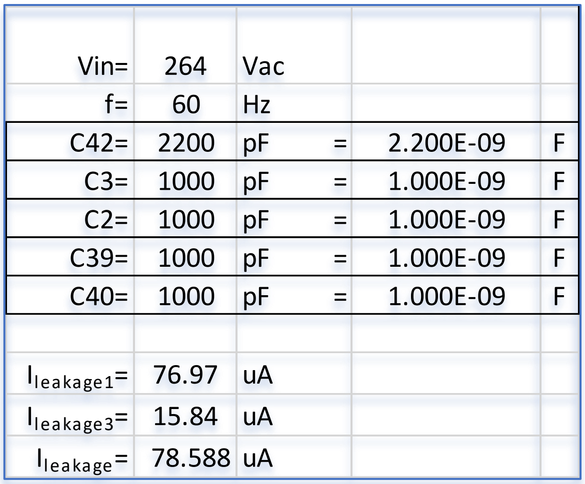
Assuming the capacitance tolerances are ±10% and ±20%, respectively, we try to find the amount of change in leakage current caused by the Y capacitance error in the medical power supply.

Solution:

According to the testing requirements for patient leakage current in IEC60601-1, the mains supply voltage should be at 110% of the highest- RATED MAINS VOLTAGE and at the highest-RATED supply frequency. This means that a product rated for operation at 115 ~ 240 Vac, 50/60 Hz would be tested at 264 Vac and a line frequency of 60Hz.

The leakage current caused by the ideal Y capacitors (without deviations) of the medical power supply can be directly obtained by using Formula (4) in Excel:

Table 1: The Leakage Current to Ground Caused by The Ideal Y Capacitors without Deviations



Vin=	264	Vac			
f=	60	Hz			
C42=	2200	pF	=	2.200E-09	F
C3=	1000	pF	=	1.000E-09	F
C2=	1000	pF	=	1.000E-09	F
C39=	1000	pF	=	1.000E-09	F
C40=	1000	pF	=	1.000E-09	F
$I_{leakage1}$=	76.97	uA			
$I_{leakage3}$=	15.84	uA			
$I_{leakage}$=	78.588	uA			

At the 264Vac input, the ideal fundamental leakage current of the power supply is 76.97uA and the third harmonic leakage current is 15.84uA. The total ideal leakage current is 88.88uA. In the case where all the Y capacitance deviations are equal to zero, the Patient leakage current can meet the requirement of less than 100uA.

A Pspice simulation circuit for Leakage Current measurement is built in Figure 5 to verify the above calculation result.

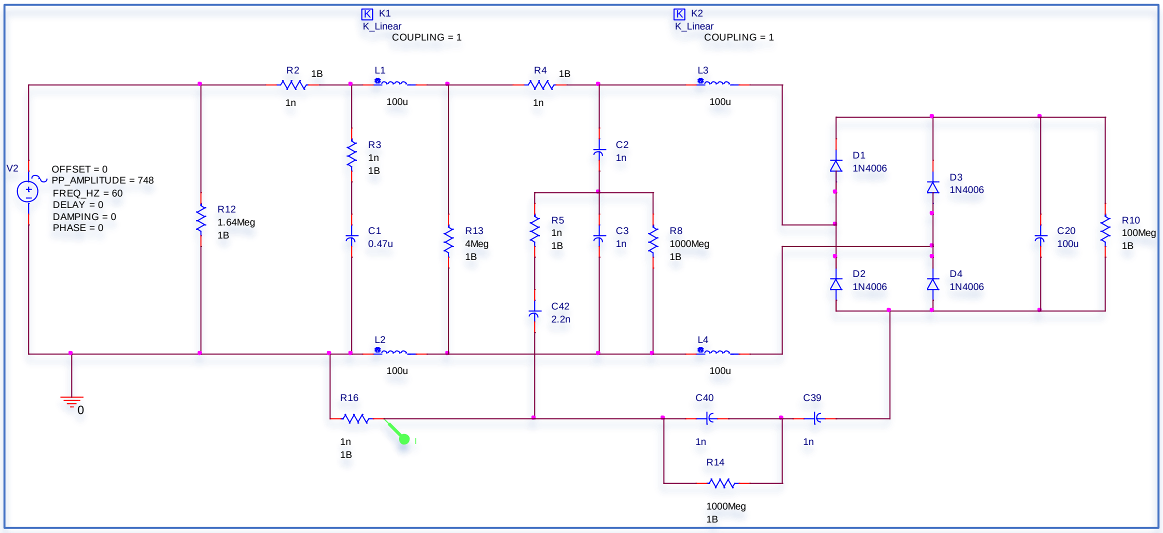


Figure 5: Simplified Pspice Simulation Circuit for Patient Leakage Current Measurement

The simulated patient leakage current measurement waveform for the ideal Y capacitors without errors is shown in Figure 6.

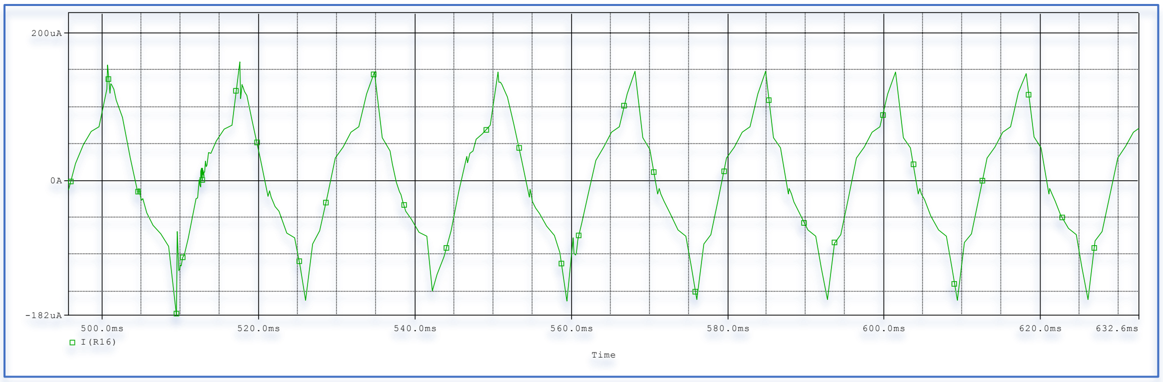


Figure 6: The Simulation Waveform for Patient Leakage Current Measurement with Ideal Y Capacitors without Errors

From Figure 6 we note that the leakage current is not a perfect sinusoidal waveform (including 3rd harmonic) due to the rectifier bridge. Its fundamental frequency component (at 60Hz) and 3rd harmonic (180Hz) are shown in Figure 7 and thus the Formula (4), (5) and (6) are good enough for leakage current estimation.

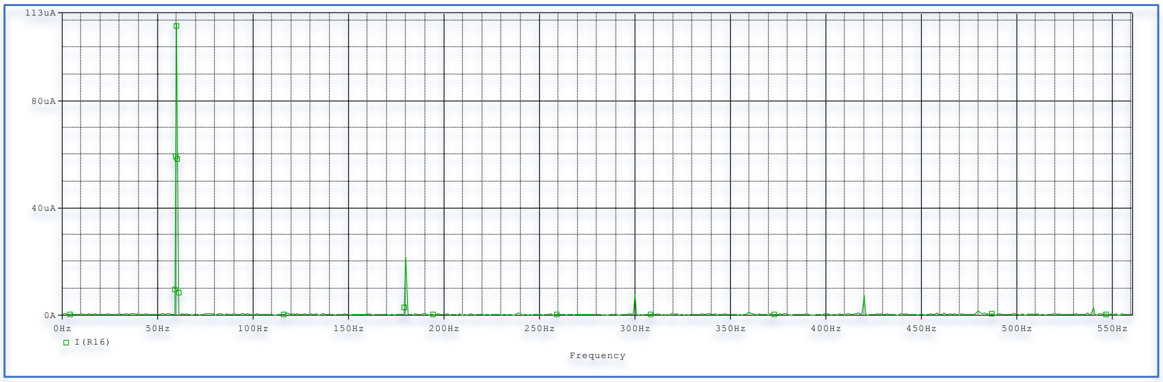
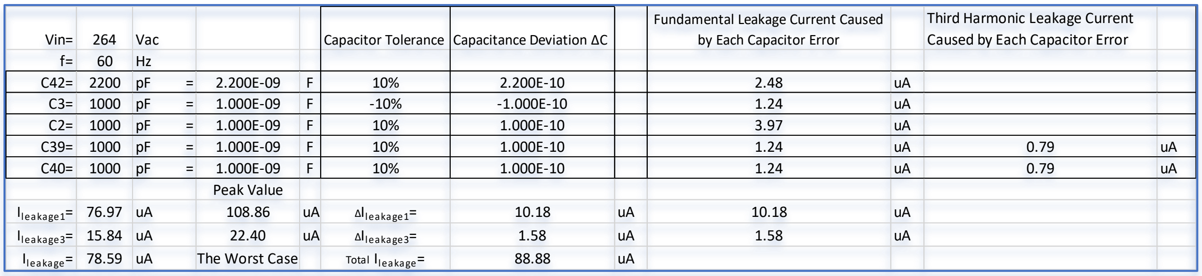


Figure 7: The FFT for Patient Leakage Current Measurement with Ideal Y Capacitors without Errors

Table 2 is the leakage current of the extreme case where C3 has -10% tolerance capacitance and the remaining Y capacitances have +10% Tolerance and calculated in Excel. It can be seen from the calculation results that in this extreme case, the leakage current caused by the Y capacitors is 88.88 uA. If considering other distributed capacitances of the power supply, such as stray capacitors in transformer coupling, choosing 10% capacitor accuracy has some margin.

Under the same 10% Y capacitance tolerance, C2 and C42 contributes the most to the leakage current. Therefore, in the component selection process, the capacitor with a better Y capacitor accuracy can be considered for C2 and C42, for example ±5% tolerance.

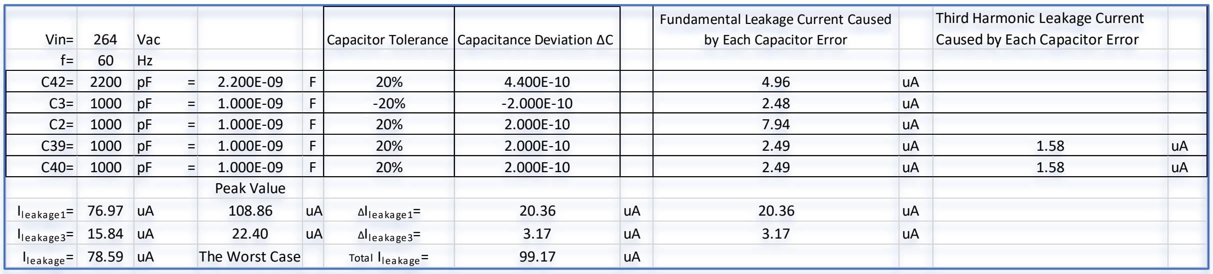
Table 2: The Leakage Current Calculated with -10% Tolerance for C3 and +10% Tolerance for All Other Y Capacitors



Vin=	264	Vac			Capacitor Tolerance	Capacitance Deviation ΔC		Fundamental Leakage Current Caused by Each Capacitor Error		Third Harmonic Leakage Current Caused by Each Capacitor Error	
f=	60	Hz									
C42=	2200	pF	= 2.200E-09	F	10%	2.200E-10		2.48	uA		
C3=	1000	pF	= 1.000E-09	F	-10%	-1.000E-10		1.24	uA		
C2=	1000	pF	= 1.000E-09	F	10%	1.000E-10		3.97	uA		
C39=	1000	pF	= 1.000E-09	F	10%	1.000E-10		1.24	uA	0.79	uA
C40=	1000	pF	= 1.000E-09	F	10%	1.000E-10		1.24	uA	0.79	uA
			Peak Value								
$I_{leakage1}$=	76.97	uA	108.86	uA	$\Delta I_{leakage1}$=	10.18	uA	10.18	uA		
$I_{leakage3}$=	15.84	uA	22.40	uA	$\Delta I_{leakage3}$=	1.58	uA	1.58	uA		
$I_{leakage}$=	78.59	uA	The Worst Case		Total $I_{leakage}$=	88.88	uA				

For further analysis, Table 3 below shows the leakage current 99.17uA in an extreme case of -20% tolerance for C3 and +20% tolerance for all other Y capacitors. In this case, the leakage current is very close to the limit 100uA in the IEC60601-1 requirements with very small margin.

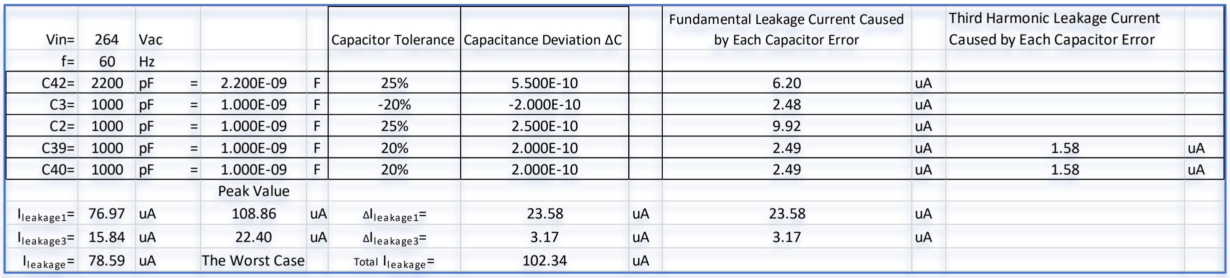
Table 3: The Leakage Current Calculated with -20% Tolerance for C3 and +20% Tolerance for All Other Y Capacitors



Vin=	264	Vac			Capacitor Tolerance	Capacitance Deviation ΔC		Fundamental Leakage Current Caused by Each Capacitor Error		Third Harmonic Leakage Current Caused by Each Capacitor Error	
f=	60	Hz									
C42=	2200	pF	= 2.200E-09	F	20%	4.400E-10		4.96	uA		
C3=	1000	pF	= 1.000E-09	F	-20%	-2.000E-10		2.48	uA		
C2=	1000	pF	= 1.000E-09	F	20%	2.000E-10		7.94	uA		
C39=	1000	pF	= 1.000E-09	F	20%	2.000E-10		2.49	uA	1.58	uA
C40=	1000	pF	= 1.000E-09	F	20%	2.000E-10		2.49	uA	1.58	uA
			Peak Value								
$I_{leakage1}$=	76.97	uA	108.86	uA	$\Delta I_{leakage1}$=	20.36	uA	20.36	uA		
$I_{leakage3}$=	15.84	uA	22.40	uA	$\Delta I_{leakage3}$=	3.17	uA	3.17	uA		
$I_{leakage}$=	78.59	uA	The Worst Case		Total $I_{leakage}$=	99.17	uA				

Finally, considering another extreme case of -20% tolerance for C3, +25% tolerance for C42 and C2, and +20% tolerance for C39 and C40 in Table 4, the leakage current is 102.34 uA which exceeds the limit 100uA in the testing requirement.

Table 4:The Leakage Current Calculated with -20% Tolerance for C3, +25% Tolerance for C42 and C2 and +20% Tolerance for All Other Y Capacitors



Vin=	264	Vac			Capacitor Tolerance	Capacitance Deviation ΔC		Fundamental Leakage Current Caused by Each Capacitor Error		Third Harmonic Leakage Current Caused by Each Capacitor Error	
f=	60	Hz									
C42=	2200	pF =	2.200E-09	F	25%	5.500E-10		6.20	uA		
C3=	1000	pF =	1.000E-09	F	-20%	-2.000E-10		2.48	uA		
C2=	1000	pF =	1.000E-09	F	25%	2.500E-10		9.92	uA		
C39=	1000	pF =	1.000E-09	F	20%	2.000E-10		2.49	uA	1.58	uA
C40=	1000	pF =	1.000E-09	F	20%	2.000E-10		2.49	uA	1.58	uA
			Peak Value								
$I_{leakage1}$=	76.97	uA	108.86	uA	$\Delta I_{leakage1}$=	23.58	uA	23.58	uA		
$I_{leakage3}$=	15.84	uA	22.40	uA	$\Delta I_{leakage3}$=	3.17	uA	3.17	uA		
$I_{leakage}$=	78.59	uA	The Worst Case		Total $I_{leakage}$=	102.34	uA				

The simulated patient leakage current measurement waveform for the Y capacitors with -20% Tolerance for C3, +25% Tolerance for C42 and C2 and +20% Tolerance for All Other Y Capacitors is shown in Figure 8. It is evident that the peak value of the simulated leakage current increases compared with that in Figure 6.

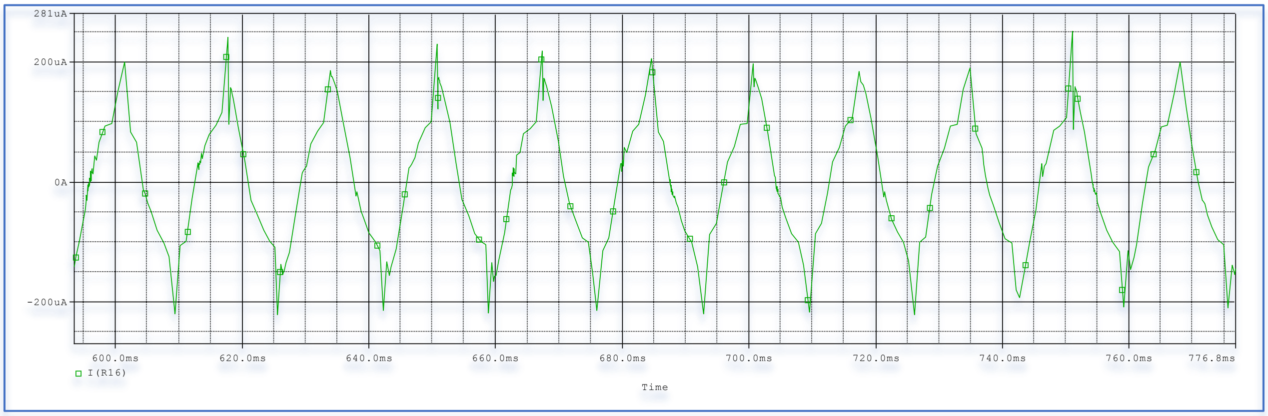


Figure 8: The Simulation Waveform for Patient Leakage Current Measurement with -20% Tolerance for C3, +25% Tolerance for C42 and C2 and +20% Tolerance for All Other Y Capacitors

From the FFT of the above leakage current waveform in Figure 9, it is clearly known that the fundamental component peak value exceeds 145uA and 3rd harmonic peak is above 25uA.

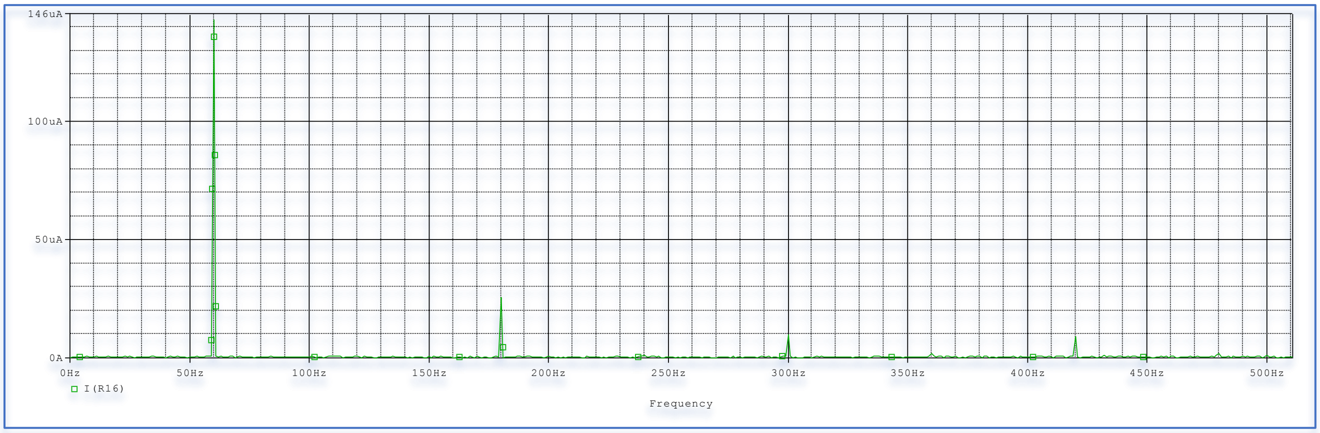


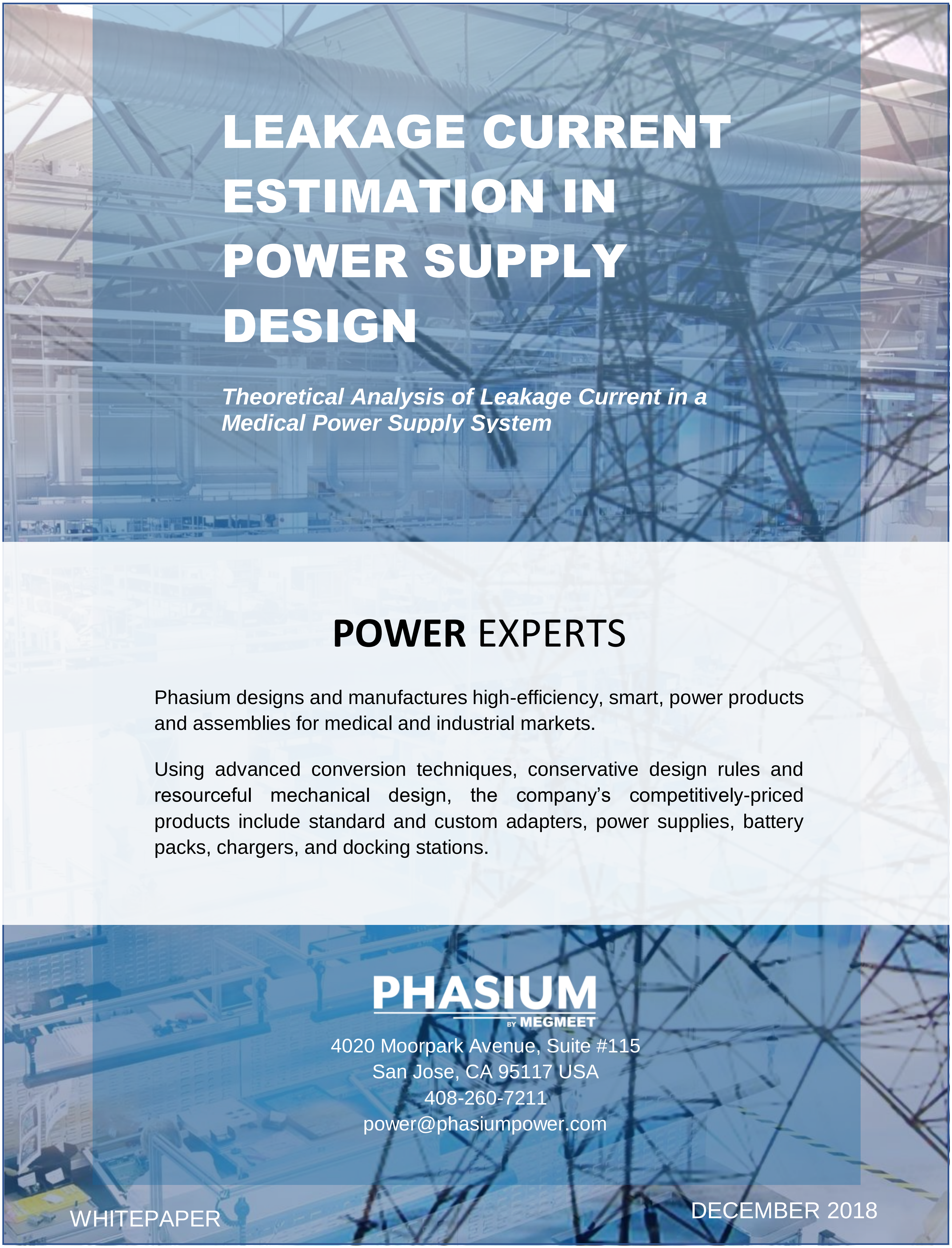
Figure 9:The FFT for Patient Leakage Current Measurement with -20% Tolerance for C3, +25% Tolerance for C42 and C2 and +20% Tolerance for All Other Y Capacitors

CONCLUSIONS

The Patient leakage current is mainly contributed by Y capacitors in the power supply design. The fundamental and third harmonic components are dominant in the leakage current. The equivalent circuit and formulae for this leakage current estimation are derived and verified by the simulations.

Using the partial differential error analysis method, the effect of each Y capacitor on the leakage current of the power supply is clearly obtained. This provides guides on the selection of each Y capacitor tolerance parameter of the power supply and the quality control in production.

Taking a medical power adaptor topology as an example to theoretically select the tolerance of the capacitor, the leakage current error is determined by the tolerances of 5 Y capacitors, that is, the output leakage current is controlled by multivariable (5 variables), and the total deviation of the multivariable circuit structure is the sum of the partial differential of the error of each component. Since the capacitors have positive and negative tolerances and are variables of the multivariable function of the leakage current of the power supply, this causes big scattering of the actual leakage current value measurement result of the power supply in production. Considering the influence of other distributed parasitic parameters of the power supply on the leakage current, the Y capacitance of the medical power adaptor should be selected with ±10% .



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POWER EXPERTS

Phasium designs and manufactures high-efficiency, smart, power products and assemblies for medical and industrial markets.

Using advanced conversion techniques, conservative design rules and resourceful mechanical design, the company's competitively-priced products include standard and custom adapters, power supplies, battery packs, chargers, and docking stations.

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