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A New System Architecture Improves Output Power Regulation in Electrosurgical Generators

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***Abstract*—A new system architecture for electrosurgical generators inherently produces the ideal electrosurgical output characteristic with near-deadbeat control. Compared to existing technology, this converter significantly improves power regulation, leading to improved surgical outcomes by minimizing thermal spread and tissue charring.**

I. INTRODUCTION

ELECTROSURGERY is the use of a high-frequency current applied directly to tissue to affect cutting, desiccation, and/or fulguration [1]. It provides benefits which are unavailable from a cold scalpel, such as hemostasis and consistent drag force.

A device known as an electrosurgical generator (“ESG”) provides high frequency AC current to the surgeon’s electrosurgical instrument. Regulation of the output power and peak voltage provided by the ESG is critical to minimizing unwanted thermal damage or charring of tissue. Yet, most commercially-available ESGs rely on circuit topologies which respond slowly to changes in tissue impedance, allowing delivered power to fluctuate, especially during arcing. This paper discusses the major problems encountered with existing ESG designs and presents an alternative system architecture that significantly improves power regulation by inherently producing the ideal ESG output characteristic, and explains how this leads to improved surgical outcomes by reducing thermal damage and tissue charring.

Section II of this paper explains the physical mechanisms present in electrosurgery and describes the ideal ESG output characteristic. Section III presents a detailed analysis of how the most common circuit topology used in ESGs is unable to respond to rapid changes in tissue impedance, resulting in poor output regulation. Section IV describes a proposed new system architecture which inherently produces the ideal ESG output characteristic, significantly improving power regulation. Finally, Section V summarizes the results.

II. THE IDEAL ESG OUTPUT CHARACTERISTIC

As electrical current passes through tissue, the tissue experiences I^2R heating and exhibits different responses depending on the temperature reached and the time interval over which the temperature rise occurs. When heated past 45°C, proteins in tissue become denatured and lose structural integrity. When heated past 90°C, water begins to evaporate — if this temperature is reached slowly, enough water can be driven off to desiccate tissue; if reached quickly, explosive vaporization occurs, causing a cutting effect. If tissue is allowed to reach 200°C, the remaining solids are reduced to carbon [2].

The electrical impedance of the complete ESG/tissue circuit varies widely with tissue type. Typical impedances encountered range from 0Ω to 4kΩ [3]. Upon taking into consideration the wide range of impedance, along with an understanding of the fundamental heating effect, it becomes clear that the ideal ESG output is a constant power source. As a practical matter, this constant power source must be limited to a maximum voltage and maximum current, as the ESG, as well as the electrosurgical instruments and leads, must be rated to carry a finite current and insulate against a finite voltage. Fig. 1 shows the ideal ESG output characteristic as an I/V plot.

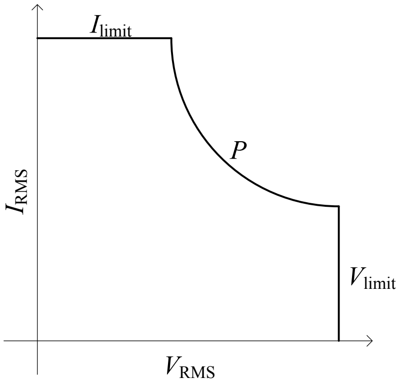

Fig. 1 – Desired output characteristic

In addition, a set maximum voltage, V_{limit}, serves to limit the length of any arcs formed. When a sufficient quantum of power is applied to a high-impedance section of tissue, high voltages can be developed which cause arcing between the electrosurgical instrument and the patient. These arcs effectively decrease the surface area of the electrosurgical instrument by striking a small area, increasing the current density experienced by said tissue, and increasing the likelihood of carbonization. Thus, control of the maximum output voltage produced by an ESG is also critically important to achieving the desired clinical results.

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III. THE PROBLEM WITH PRIOR-ART ESGS

Most commercially-available ESGs rely on a resonant inverter output stage. Resonant inverters are known to produce an elliptical equilibrium output characteristic [4], as shown in Fig. 2.

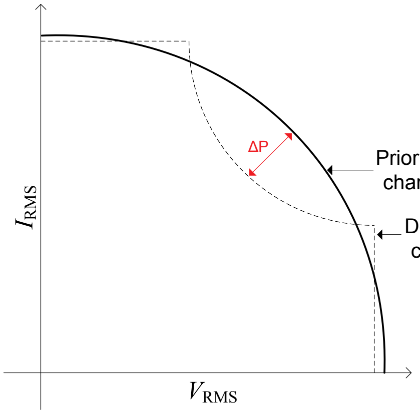

Fig. 2 – Prior-art output characteristic

The resonant inverter's elliptical output characteristic is a reasonable approximation of the ideal ESG output characteristic, as it tends to exhibit a current-source-like output at low impedances, and a voltage-source-like output at high impedances, but the ellipse deviates significantly from the desired (hyperbolic) output at mid-range impedances. These mid-range impedances, where constant power is desired, represent the vast majority of tissues encountered, resulting in frequent deviation from the desired constant-power output. Under transient conditions, the resonant inverter may exhibit even more substantial deviations.

To correct for these deviations, manufacturers add closed-loop control systems to the resonant inverter, as shown in Fig. 3.

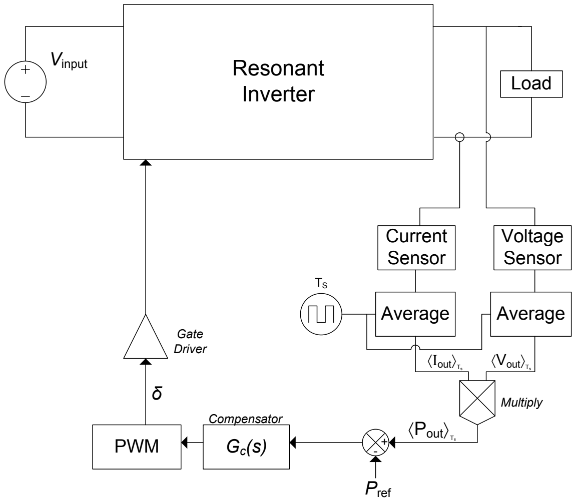

Fig. 3 – Resonant inverter with closed-loop control

Sensors on the output of the ESG measure the magnitudes of the output voltage and current. Since the output is AC, these measurements need to be averaged over a full output cycle (in practice, electrical noise forces the averaging of many tens or hundreds of cycles in order to obtain useful measurements). The averaged magnitudes of output voltage and current are then multiplied to determine the average apparent output power, which is compared to the desired output power, and the error between requested and delivered power is fed to a compensator network. The resulting signal commands a pulse-width-modulator ("PWM") to change the control signal given to the resonant inverter, which results in a change in the size of the elliptical equilibrium output characteristic.

Because of the need to measure many tens or hundreds of output cycles, along with the typically slow dynamics of the control loop and resonant inverter itself, the speed of the entire control system is often orders-of-magnitude slower than the converter AC output. Many ESG manufacturers even advertise that their machines "measure *x* changes in tissue impedance per second", even though "*x* changes per second" often represents a frequency of measurement that is two or three orders-of-magnitude slower than the frequency at which the converter operates.

The use of this slow, low-bandwidth control system results in substantial deviations of the per-cycle delivered power from the desired value. While the average power delivered over many thousands of cycles may be correct, any individual AC output cycle is unlikely to accurately deliver the requested output power. Using a popular, state-of-the-art ESG employing a resonant output stage and control loop, as previously described, human tissue analogs were dissected while measuring ESG output voltage and current. Per-cycle output power was calculated using MATLAB®, resulting in Fig. 4, a histogram of the power delivered in each output cycle. While the power requested (50W) was correct when averaged over 2,300 output cycles, the standard deviation in power delivered by any individual output cycle was 13W, and some values exceeded 120W.

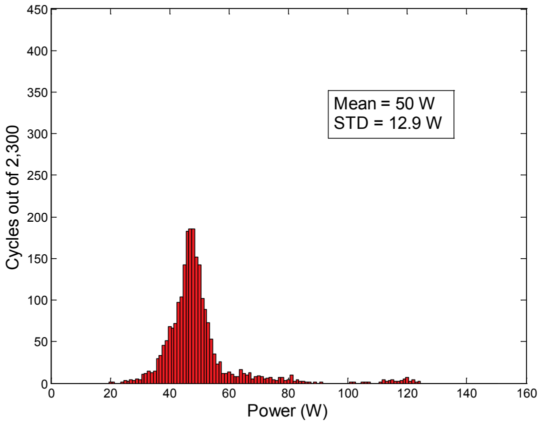

Fig. 4 – Histogram of cycle-by-cycle output power

The clinical implications of this error are significant. Excessive power delivery leads to increased thermal spread. Variation in delivered power causes inconsistent speed of cutting and drag force. Excessive peak voltages lead to undesirable tissue carbonization (charring), as shown in Fig.

5, where human tissue analogs were dissected using the same average power, but different peak voltages.

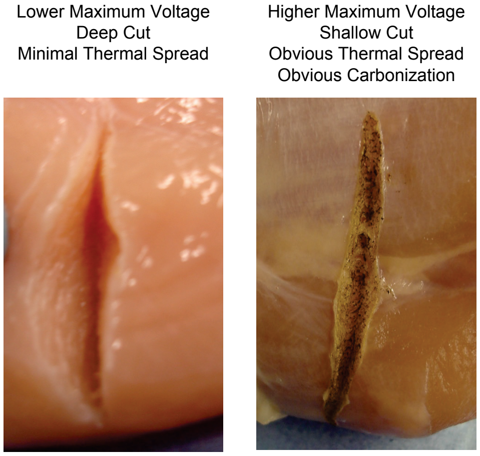

Fig. 5 – Dissection of human tissue analogs

Thus, it is clear that improvement in the performance of ESGs can be realized by improving cycle-by-cycle compliance between the requested and delivered output power.

IV. A NEW ESG ARCHITECTURE THAT INHERENTLY PRODUCES THE DESIRED OUTPUT CHARACTERISTIC

To improve cycle-by-cycle compliance between requested and delivered output power, a new system architecture for an ESG is proposed that inherently produces the desired output characteristic. The schematic diagram of the proposed ESG is shown in Fig. 6.

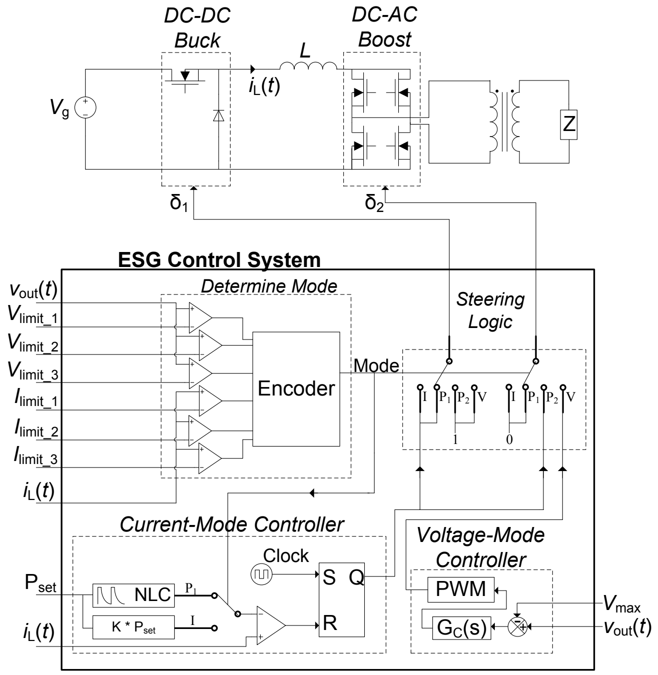

Fig. 6 – Proposed new ESG system architecture

The circuit of Fig. 6 breaks the ideal output characteristic into four different regions, as shown in Fig. 7 and described below.

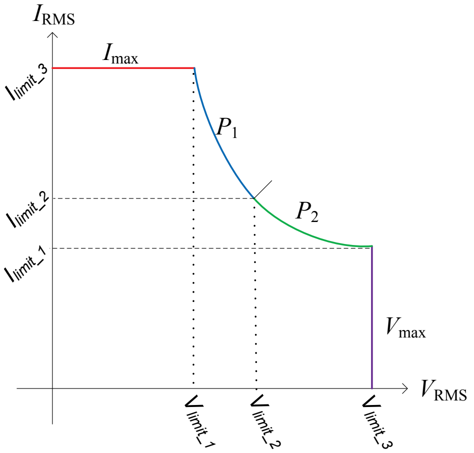

Fig. 7 – Four regions of desired output characteristic

A. *Current-Limited Mode (“I_{max}”)*

In current-limited mode, the DC–AC boost converter is given a fixed duty cycle, causing it to invert the DC output current of the DC–DC buck converter into an AC current of peak amplitude I_{max}. The DC–DC buck converter is operated in current-programmed mode (“CPM”) with a fixed control limit. CPM of a buck converter is known to produce a current-source output characteristic [5]. Thus, the converter produces an AC constant-current output.

B. *Constant-Power Modes (“P_1” and “P_2”)*

The constant-power region spans a wide impedance range (from around 50Ω to 4kΩ). Realization of a single-stage converter capable of operating over such a wide load range is difficult; the constant-power region is thus broken into two smaller regions.

1) *Constant Power region “P_1”*

In the “P_1” region, the buck converter is operated with peak current-mode nonlinear-carrier (“NLC”) control [6]. The carrier is chosen such that the average power delivered by the buck stage is constant, on a cycle-by-cycle basis. The DC–AC boost stage operates with constant duty cycle; since this stage is power conservative it outputs constant AC power independent of load resistance.

2) *Constant Power region “P_2”*

In the “P_2” region, constant power is obtained from the CPM-controlled DC–AC boost converter, using a linear control limit. CPM-control of a two-switch boost converter is known to produce a DC power source output [7], and by extension, a four-switch (full bridge) boost converter can be used to produce an AC power source output.

C. *Voltage-Limited Mode (“V_{max}”)*

In the voltage-limited mode, the DC–DC buck converter is bypassed, and the DC–AC boost converter is regulated using a standard pulse-width-modulated (“PWM”) controller. A high-speed, low-latency ADC and sensor on the output transformer measures $v_{out}(t)$, and an digital average of peak values produces a reasonably linear measurement that is available to the controller within the same switching cycle.

The “*Determine Mode*” block measures $v_{\text{out}}(t)$ and $i_L(t)$, and by comparison to programmed setpoints ($V_{\text{limit\_1,2,3}}$ and $I_{\text{limit\_1,2,3}}$) directs the outputs of the current-mode controller and voltage-mode controller to the appropriate converter stage. Thus, the circuit of Fig. 6 inherently realizes the ideal ESG output characteristic. Additionally, unlike with prior-art resonant inverters, this ESG can be arbitrarily programmed in regards to maximum voltage, power, and current, as well as to setpoints which determine the impedance at which transitions between modes occur.

Fig. 8 shows a plot of *I/V* data taken from a prototype ESG constructed using the system architecture of Fig. 6.

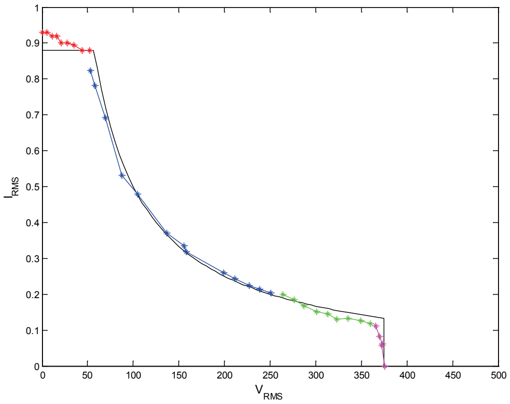

Fig. 8 – Experimental data overlaid on ideal ESG output curve

While prior-art ESGs rely on sampling and averaging many tens or hundreds of output cycles before engaging the control loop, this ESG achieves near-deadbeat regulation by using a cycle-by-cycle comparison in the current-mode controller. Fig. 9 shows a load step in impedance, and demonstrates that the control system is capable of regulating within one or several cycles.

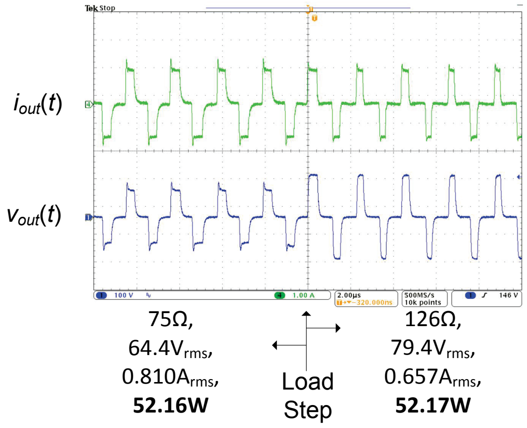

Fig. 9 – Output voltage and current during load step

Fig. 10 shows a histogram of the power delivered in each output cycle from a prototype ESG employing current-mode control of the constant-power output, as described above. The standard deviation of power in each output cycle was 2.4W, a significant improvement over the 13W standard deviation observed in Fig. 4. The large amplitude (~120W) peaks are absent.

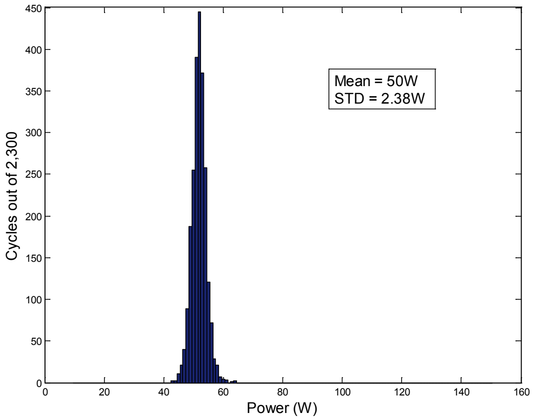

Fig. 10 – Histogram of new converter cycle-by-cycle output power

V. CONCLUSION

This paper presents a new ESG system architecture that inherently produces the desired output characteristic with near-deadbeat control. This represents a significant improvement over prior-art ESGs, which typically employ very slow control loops that allow cycle-by-cycle power to vary dramatically.

High-speed regulation of ESG output power minimizes thermal spread and associated tissue damage. Additionally, limiting peak voltages serves to control the length of arcs formed, which allows control of tissue carbonization. The ability to arbitrarily program maximum current, voltage, power, and impedances at which transitions occur, should prove to be a powerful tool for improving the management of tissue damage in electrosurgery.

REFERENCES

[1] L. E. Curtiss, “High frequency currents in endoscopy: A review of principles and precautions,” *Gastrointestinal Endoscopy,* vol. 20, no. 1, pp. 9-12, Aug 1973.

[2] N. N. Massarweh, N. Cosgriff, D. P. Slakey, “Electrosurgery: History, Principles, and Current and Future Uses,” *J Am Coll Surg.* 2006 Mar;202(3):520-30.

[3] T. J. Faes, H. A. van der Meij, J. C. de Munck, R. M. Heethaar, “The electric resistivity of human tissues (100 Hz-10 MHz): a meta-analysis of review studies,” *Physiological Measurement*, vol. 20 no. 4, pp. 1-10, Nov 1999.

[4] M. Gulko and S. Ben-Yaakov, “Current-Sourcing Push-Pull Parallel-Resonance Inverter (CS-PPRI): Theory and Application as a Fluorescent Lamp Driver,” *IEEE Applied Power Electronics Conference*, 1993 Record, pp. 411-417.

[5] C. W. Deisch, “Simple Switching Control Method Changes Power Converter Into A Current Source,” *IEEE Power Electronics Specialists Conference - 1978 Record*, pp. 300-306

[6] D. Maksimovic, Y. Jang, and R. Erickson, “Nonlinear-Carrier Control for High Power Factor Boost Rectifiers,” *IEEE Applied Power Electronics Conference*, 1995 Record, pp.635-641

[7] R. D. Middlebrook, “Modeling Current Programmed Buck and Boost Regulators,” *IEEE Transactions on Power Electronics*, Vol. 4, No. 1, Jan 1989, pp. 36-52.