HIGH VOLTAGE CONVERTER MODULATOR OPTIMIZATION*

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Abstract

High voltage converter modulators (HVCM) are at the forefront of long pulse high voltage (100kV) technology for Klystron voltage sources. We present results of digitally implementing an extremum seeking (ES) algorithm with which we optimized the rise time of the output voltage of a HVCM at the Los Alamos Neutron Science Center (LANSCE) HVCM test stand by iteratively, simultaneously tuning the first 8 switching edges of each of the three phase drive waveforms (24 variables total). We achieved a 50us rise time, which is reduction in half compared to the 100us currently achieved at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory. The ES algorithm is successful despite the noisy measurements and cost calculations, confirming the theoretical predictions that the algorithm is not affected by noise unless it both matches exactly the frequency components of the controller's specific perturbing frequencies and is of comparable size.

BACKGROUND ON HIGH VOLTAGE CONVERTER MODULATOR

High Voltage Converter Modulators (HVCM) offer significant performance advantages over conventional modulator technologies for long pulse applications [1]. A simplified schematic of a typical HVCM is shown in Figure 1. Direct modulation of a switching power supply is used to produce the pulse. A high frequency transformer incorporated into the supply is used to step-up from voltages suitable for the semiconductors, to those required by the load. Three input H-Bridges (only one is shown in Figure 1) are connected to a common DC-link capacitor (not shown). The output of each H-Bridge is connected to the primary winding of a high voltage transformer. The transformer secondary windings are connected in 'Y' and to the output rectifier and filter.

A steady state analysis of the HVCM is presented in [2]. However, the interaction between the high frequency resonant components and the output filter make it very difficult to analyze the circuit under transient conditions. Therefore in order to optimize the rise time of the output voltage across the load the first eight switching edges of the three phase drive waveforms of each of the three input H-Bridges were perturbed according the extremum seeking scheme outlined in this paper.

OVERVIEW OF OPTIMIZATION SCHEME

The ES algorithm was implemented in real-time computer code running on an embedded hardware platform based on the Texas Instruments TMS320F28335 Digital Signal Controller. Compared to the currently achievable rise time of $100\mu s$ for the HVCMs, the improvement achieved is a $2\times$ reduction.

We denote by $V(n,t)$ the measurable HVCM output voltage at time t for parameter settings $p_{i,j}(n)$, where $p_{i,j}$ is the i$^{\text{th}}$ edge of the j$^{\text{th}}$ waveform's switching edges, as shown in Figure 2.

For any $t \in [t_0, t_0 + t_r + T_1]$, as shown in Figure 3 the output voltage has dynamics as described by some unknown function $F(V(n,t), P(n))$, where $P(n) = \{p_{i,j}(n)\}$. For $t \in [t_0 + t_r + T_1, t_0 + t_r + T_1 + T_2]$ the embedded hardware has T_2 seconds to perform calculations and update the parameter values $p_{i,j}(n+1)$.

Based on the results of [3, 4], in order to minimize a cost function, as suggested by Lie bracket averaging results (discussed in more detail below) the iterative tuning law for the parameters $p_{i,j}(n)$ was chosen as:

$$\begin{aligned} p_{i,j}(n+1) \quad &= \quad p_{i,j}(n) + \alpha\sqrt{\omega_{i,j}} \cos\left(\omega_{i,j} n dn\right) dn \\ &\quad -k\sqrt{\omega_{i,j}} \sin\left(\omega_{i,j} n dn\right) C(n) dn, \quad (1) \end{aligned}$$

where we have defined the cost function

$$C(n) = \int_{t_1}^{t_2} \left(V(n,\tau) - V_{\text{ref}}\right)^2 d\tau, \qquad (2)$$

where t_1 is the desired rise time and t_2 is chosen such that $t_1 < t_2 \leq T_1$ and is a long enough time so that the system has reached steady state.

Note 1 *In the update law (1) we also implemented constraints, such as avoidance of placing two switching edges on top of each other. One such rule was given as:* **If** $p_{i,j}(n+1) = p_{i,j+1}(n+1)$, **Then** $p_{i,j}(n+1) = p_{i,j}(n)$.

The update law (1) is chosen with $dn \ll 1$ sufficiently small relative to the perturbation periods $T_{i,j} = \frac{2\pi}{\omega_{i,j}}$ so that based on the finite difference approximation of a derivative the system's n-dynamics approximately satisfy

$$\frac{\partial p_{i,j}}{\partial n} = \alpha\sqrt{\omega_{i,j}} \cos\left(\omega_{i,j} n\right) - k\sqrt{\omega_{i,j}} \sin\left(\omega_{i,j} n\right) C, \quad (3)$$

$$\frac{\partial C}{\partial n} = \sum_{i,j=1}^{m} \frac{\partial C}{\partial p_{i,j}} \sqrt{\omega_{i,j}} \left(\alpha \cos(\omega_{i,j} n) - k \sin(\omega_{i,j} n) C\right). \qquad (4)$$

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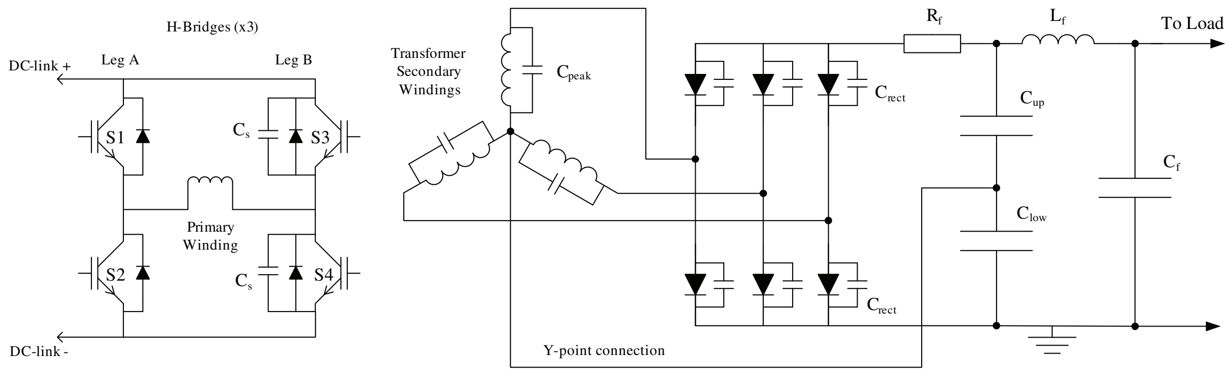

Figure 1: Simplified schematic of a typical HVCM. The primary windings of the three H-Bridges, shown on the left, are connected to the secondary windings in a 'Y' shown on the right.

For large values of $\omega_{i,j}$, we can associate with system (3), (4) the averaged system:

$$\frac{\partial \bar{p}_{i,j}}{\partial n} = -\frac{k\alpha}{2}\frac{\partial \bar{C}}{\partial \bar{p}_{i,j}}, \quad \bar{p}(n_0) = p(n_0), \tag{5}$$

$$\frac{\partial \bar{C}}{\partial n} = -\frac{k\alpha}{2}\sum_{i,j=1}^{m}\left(\frac{\partial \bar{C}}{\partial p_{i,j}}\right)^2, \quad \bar{C}(n_0) = C(n_0) \tag{6}$$

see [3, 4, 5] for details.

Note 2 *On the choices of ω, k, and α.*

The term $\alpha\sqrt{\omega_{i,j}}\cos(\omega_{i,j}n)$ in (3) can be thought of as the perturbing dither term. Unlike the $-k\sqrt{\omega_{i,j}}\sin(\omega_{i,j}n)C(n)$ term, which decreases with decreased cost, the α term is always present, with an amplitude of (after integration) $\frac{\alpha}{\omega_{i,j}}$. Therefore, either a very small value of α or a very large value of the $\omega_{i,j}$ is required in order for the tuned parameters $p_{i,j}$ to settle near optimal set-points as the cost function is minimized. Simply choosing a very small value of α introduces difficulties because the overall system, on average, converges at a rate proportional to the product $k\alpha$.

In practice, a reasonable α is first chosen (by trial and error) and then a much larger value of k is also chosen, so that the product $k\alpha$ gives reasonably fast convergence, with the large k term vanishing as the cost function is decreased. The value of the $\omega_{i,j}$ are increased until stability and a desired level of convergence (relative to the size of α) is achieved.

Theoretically, the choices of $\omega_{i,j}$ must be distinct to satisfy the requirements of the Lie bracket averaging. In practice the choices of $\omega_{i,j}$ should further satisfy the property that for all distinct $\omega_{i,j}$, $\omega_{i_1,j_1} \neq \omega_{i_2,j_2} \pm \omega_{i_3,j_3}$, to prevent mixed signals in the nonlinear system from creating harmonics which cause cross talk between different components. The frequencies $\omega_{i,j}$ must be large relative to the values of k and α. Once $C(n)$ has reached a desired level at some iteration n_2 the extremum seeker is turned off, with parameter settings fixed at the constant values $p_{i,j}(n > n_2) \equiv p_{i,j}(n_2)$.

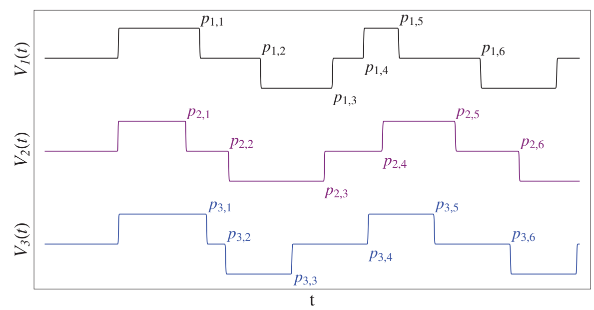

Figure 2: $p_{i,j}$ is the j^{th} switching edge of the i^{th} drive waveform V_i of each of the three input H-Bridges (as shown in Figure 1). The extremum seeker tunes only the first 8 switching edges of each drive waveform, which influence the rise time. The other waveforms are maintained at pre-calculated values.

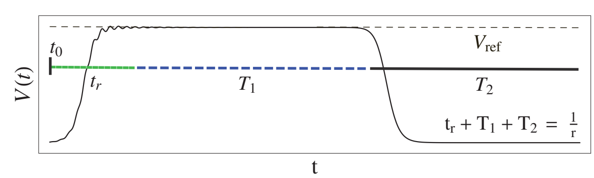

Figure 3: The HVCM is periodically activated with rise time t_r and pulse width T_1 defined such that $|V(t) - V_{\text{ref}}| < \frac{|V_{\text{ref}}|}{100}$ for all $t \in [t_r, t_r + T_1]$. The HVCM is then turned off for a length of time T_2 such that the period T of one operation cycle is equal to $t_r + T_1 + T_2 = \frac{1}{r}$, resulting in r pulses per second.

EXPERIMENTAL RESULTS

Throughout the experiments, the desired output voltage was set at $V_{\text{ref}} = -10kV$, a voltage low enough to allow a 60Hz repetition rate with the available load. After optimization, with parameters fixed at their optimal settings, the voltage was turned up to approximately -50kV and the HVCM was again triggered to generate a pulse and confirm the desired output voltage performance.

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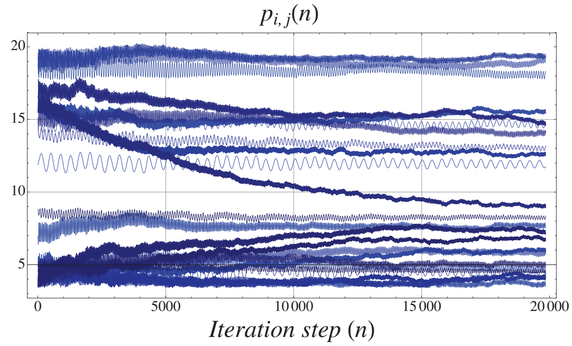

Figure 4: The evolution of the switching edges of the driving waveforms V_1, V_2, and V_3 during the extremum seeking optimization. Pulse widths are shown in microseconds.

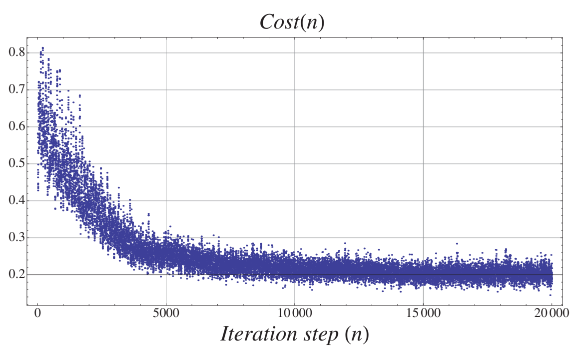

Figure 5: A less noisy cost was detected in the computer in $n = 20,000$ steps when each iterative extremum seeking step calculated the cost based on the average of 10 HVCM shots with fixed settings.

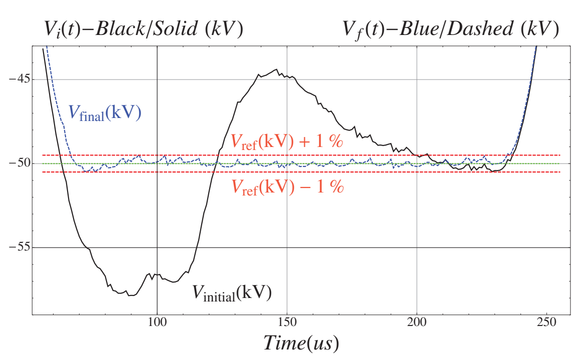

Figure 6: Using the averaging scheme and 8 edges per driving waveform the final output voltage was within 1% error after extremum seeking was completed.

Following the tuning experiments, discussed in detail below, the HVCM was fired at -90kV, a quantity limited by both the available power sources and current load setup, confirming $< 1\%$ error.

In the initial experiments, the iterative update scheme (1) was performed after every single firing of the HVCM. This resulted in convergence to within $\pm 1.5\%$ error of the output voltage, at which point noise levels became comparable to the controller induced perturbations.

In order to mitigate the effects of the random noise, the cost was replaced by an averaged value $\bar{C}(n)$,which was calculated by averaging 10 cost measurements $C(n_1), \ldots, C(n_{10})$, each calculated as:

$$C(n_i) = \int_{t_1}^{t_2} \left(V(n_i, \tau) - V_{\text{ref}}\right)^2 d\tau, \qquad (7)$$

where the parameters $p_{i,j}(n_i)$ were kept constant during the ten averaging shots $n_1, \ldots, n_{10}$, where $t_1 = 50\mu s$, $t_2 = 100\mu s$ is sufficiently large to capture voltage transients, $k = 400$, $\alpha = 0.01$, and the voltage output $V(t, n_i)$ depends on the parameter settings $p_{i,j}(n_i)$ at step n_i.

The perturbing angular frequencies $\omega_{i,j}$ of the parameters $p_{i,j}$ were all on the order of 50000 and $\delta = 5 \times 10^{-7}$, so that $\frac{\max_{i,j}\{\omega_{i,j}\}}{2\pi}\delta < \frac{1}{16}$, guaranteeing that on the n-time scale the sines and cosines are smooth, with at least 16 points per 2π phase advance for the highest frequency. The evolution of the cost function $C(n)$ over $n = 20,000$ averaged iterative steps (200,000 actual steps), which is 200,000$T \approx 1$ hour of real time optimization (the HVCM with a rep rate of $60Hz$, which was limited by the available load), is shown in Figure 5. The voltage is then turned up to $-50kV$ and a comparison of the initial and final output voltage waveforms is shown in Figure 6. The output voltage error was brought within the desired $< 1\%$ range. Figure 4 shows the evolution of the perturbed pulse widths (in microseconds) of the driving waveform V_1, V_2, and V_3 during the extremum seeking optimization process.

CONCLUSIONS

The scheme presented is model independent, it only needs to sample a cost, and is therefore very general and may be useful for optimization of many systems, such as beam parameters based on magnet or RF tuning.

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