Trapezoidal and Triangular Waveform Profiles for Reducing Power Dissipation in Liquid Crystal Displays

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***Abstract*—We propose to replace the rectangular select pulses in all the conventional addressing techniques with either trapezoidal or triangular select waveforms to reduce the power dissipated in rms responding liquid crystal displays. A realistic analysis that includes the distortion in the addressing waveforms is presented for trapezoidal, triangular profiles, as well as their equivalents in discrete domain viz. the multi-step profiles and the results are compared. Good brightness uniformity among pixels that are driven to same state is achieved as a spinoff of the analysis and application of a correction voltage at the end of the select pulses. Increase in hardware complexity and the cost is minimal because just the voltage level generator circuit is modified to achieve reduction in power dissipation with new waveform profiles.**

***Index Terms*—Addressing, low-power, matrix displays, multiplexing, scanning.**

I. Introduction

Liquid crystal displays (LCDs) consist of pixels (non-emissive light valves) that modulate the light passing through them. Low power consumption and low voltage operation are the main advantages of LCDs in portable and mobile applications. Although they consume less power as compared to other types of displays, it is advantageous to extend the battery life by minimizing power dissipation in displays of portable devices. Power dissipation in LCDs is primarily due to the dissipation in resistors of the driver circuit and it depends on the addressing technique, scanning sequence, and the state of the pixels. Most of the addressing techniques have just a few voltages in the addressing waveforms so that the hardware complexity and cost of row as well as column drivers is low. Therefore, addressing waveforms have abrupt transitions and they can be viewed as concatenation of a set of pulses of different amplitudes. However, such waveforms are not advantageous from the point of power consumption. Current through the output resistance of drivers has large surges that fall off exponentially during transitions and these surges contribute to excessive power dissipation in the driver circuit. Molecules in LCDs are slow to respond to the electric field and, therefore, shape of the waveform across the pixel is relatively less important than the root mean squared voltage across it. Hence, there is scope to change the waveform profile without compromising the performance. We show that it is possible to achieve reduction in power consumption without increasing the hardware complexity of the drivers. A triangular or a trapezoidal voltage profile can be used to deliver the same energy to the pixels with less dissipation as compared to a pulse. We propose to use these profiles in all the addressing techniques to reduce power consumption. Our analysis includes the distortions in the waveforms due the *RC* time constant of the driver circuit and, hence, could be used even when the time constant of the circuit is high resulting in distorted, nonideal waveforms across the pixels.

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II. Background

Power dissipation is estimated by modeling the matrix LCD as a 2-D array of capacitors formed by sandwiching liquid crystal mixture (dielectric material) between two sets of electrodes (address and data electrodes or lines) that are orthogonal to each other (see [3, Fig. 1]). However, the capacitance of pixels in the ON (C_{on}) and OFF (C_{off}) states are different because liquid crystal molecules have shape anisotropy (hence, dielectric constant measured along the long axis of the molecule is different from that along the other two perpendicular directions) and the orientation of molecules is different in the two states. Addressing the matrix display involves repeated charging and discharging of the pixels (capacitors) to voltages that depend on the state of the pixels and the addressing technique. Power that is dissipated in the output resistance of the driver circuit is proportional to square of the amplitude of the transition in voltage across the pixel. Therefore, avoiding abrupt changes and introducing smooth transitions in the waveforms can reduce power dissipation. An analysis of power dissipation in multiplexed and non-multiplexed liquid crystal displays can be found in [1]–[3]. In a matrix display, each column is independent of other columns and equivalent circuit of a pixel in a column is shown in Fig. 1. While it may appear that it is difficult to analyze the effect of a waveform profile on power consumption because the capacitances of the pixels depend on the actual image in that column; it is adequate to perform the analysis on a simple *RC* circuit (because each current loop is just an *RC* circuit) to estimate the relative performance of different profiles and the result will hold good for both multiplexed and non-multiplexed displays, as shown in [3]. Several waveform profiles to reduce power consumption were proposed in the past viz. multi-steps [3], triangular and trapezoidal waveforms [4]. A trapezoid reduces to a triangle when the duration of the flat top is zero and hence, triangular waveforms can be treated as a special case of trapezoidal waveform. Our main objective is to analyze the power dissipation in LCDs, after including the distortions due to time constant in the driver circuit when pulses

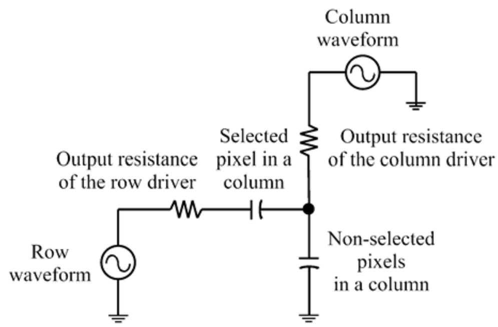

Fig. 1. Equivalent circuit of a column in a matrix display.

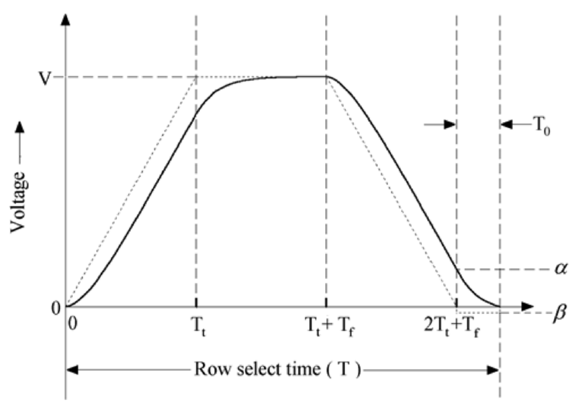

Fig. 2. A pulse of amplitude V_p in any addressing technique can be replaced by the trapezoidal waveform profile shown here to reduce power consumption.

in the addressing waveforms are replaced by either trapezoidal or triangular or the distorted multi-step waveform profiles and compare the results.

III. Analysis of the Trapezoidal Select Profile

Let us consider a trapezoidal profile shown by dotted lines in Fig. 2. The select pulse in any addressing technique can be replaced with this profile to reduce power consumption. The four segments of trapezoidal waveforms are as follows:

1) a linear ramp with a positive slope during 0 to T_t.
2) a flat region of voltage V during T_t to $(T_t + T_f)$.
3) a linear ramp with negative slope during the interval $(T_t + T_f)$ to $(2T_t + T_f)$.
4) a flat region of zero voltage during the period $(2T_t + T_f)$ to $(2T_t + T_f + T_o)$.

Here $T = (2T_t + T_f + T_o)$ is the duration of the select pulse and T_0 is introduced so that the voltage is forced to zero by discharging the pixels even when the *RC* time constant of the circuit is large. Let us consider applying this waveform profile to an *RC* circuit. Assuming the time constant due to the output resistance (*R*) of the driver circuit and the capacitance (*C*) of the pixel to be τ; the expression for the voltage across the pixel in the region 0 to T_t is given by

$$V_{\text{pixel}}(t) = \left(\frac{V}{T_t}\right) t - \left(\frac{V}{T_t}\right) \tau \left(1 - e^{-(t/\tau)}\right) \tag{1}$$

where V is the peak amplitude of the trapezoidal waveform, as shown in Fig. 2. The first term in (1) represents the ascending input ramp waveform with slope (V/T_t), while the second term represents the voltage drop across the resistor that has dependence on the time constant τ. Similarly the voltage across the pixel during the interval $(T_t + T_f)$ to $(2T_t + T_f)$ is given by

$$V_{\text{pixel}}(t_1) = \left(\frac{V}{T_t}\right) \Bigg\{ (T_t - t_1) + \tau \left[1 - \left(1 + e^{-T_f/\tau} - e^{-(T_t + T_f/\tau)}\right) e^{-t_1/\tau}\right] \Bigg\}. \tag{2}$$

wherein $t_1 = t - (T_t + T_f)$. The peak amplitude (V) of the trapezoidal waveform is greater than the amplitude (V_p) of a rectangular pulse of the conventional addressing techniques when the energy delivered during the select time is same for both the profiles. The factor by which (V) is greater than (V_p) is obtained by equating the energy delivered by the trapezoidal waveform with that of a single pulse of amplitude (V_p) over select time (T). The ratio (V/V_p) is given by

$$\frac{V}{V_p} = \sqrt{\frac{3(2T_t + T_f + T_o)}{(2T_t + 3T_f)}}. \tag{3}$$

Power dissipated in the circuit (mostly in the ON resistance of a driver) during this period can be obtained by estimating the energy delivered to the pixel during the select time T in four parts as given in

$$E_{RC\text{-distortion}} = E_1 + E_2 + E_3 + E_4 \tag{4}$$

wherein E_1, E_2, E_3, and E_4 are obtained by integrating the square of the instantaneous voltage across the pixel during the four time intervals. Voltage across the pixel can be forced to reach zero (non-select voltage) at the end of T by applying a negative voltage of amplitude β during T_o; as described in Section V to avoid crosstalk and to improve brightness uniformity of pixels that are driven to the same state. The rms voltage across the pixel will be less due to distortions in the waveform and forcing the voltage to zero at the end of T. Peak amplitude of the trapezoidal waveform profile is increased to compensate the reduction in the rms voltage. The following features have been incorporated in our analysis.

1) Negative voltage of amplitude β is applied during T_o to force the waveform profile to reach the non-select voltage at the end of T.
2) Peak voltage of waveform profile is increased to achieve the same rms voltage as a pulse of duration T.

Power dissipation due to the trapezoidal waveform is compared with that of a single pulse in Fig. 3. The *RC* time constant is assumed to be $0.05T$. The range of T_f (the duration of the peak voltage) is restricted to $(0.1T)$ and $(T - T_o - 0.1T)$. Power dissipation of the trapezoidal waveform increases with increase in T_o. These plots have a minimum, with power consumption increasing for large and small values of T_f. Percentage increase in peak voltage of the trapezoidal waveform as compared to a single pulse is plotted in Fig. 4 as a function of T_f for $\tau = 0.05T$. The peak voltage decreases with increase in T_f as evident from Fig. 4. Multi-step waveform profile [3] is briefly reviewed in Section IV before presenting the analysis of multi-step profile with distortions.

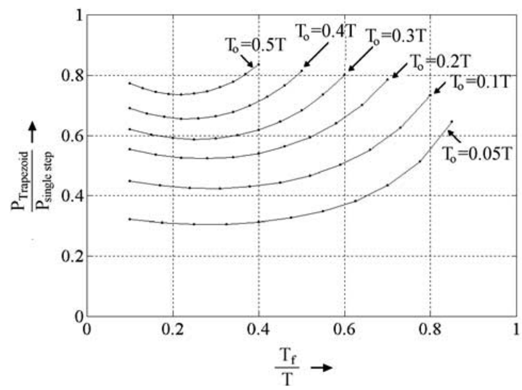

Fig. 3. Power dissipation of the trapezoidal waveform as compared to that of a single pulse for different values of T_f and T_o assuming $\tau = 0.05T$.

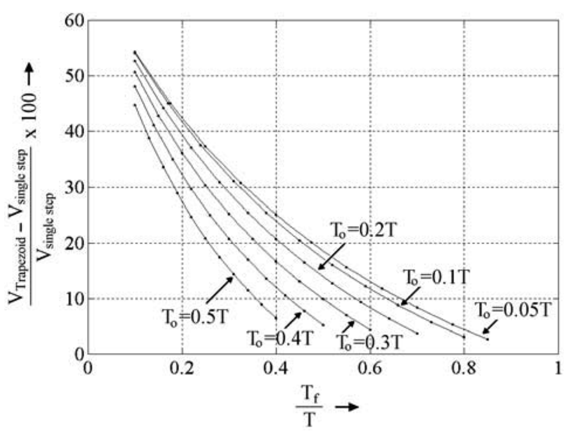

Fig. 4. Percentage increase in peak voltage of a trapezoidal waveform as compared to that of a single pulse for different values of T_f and T_o assuming $\tau = 0.05T$.

IV. Review of Multi-Step Waveform Profile

Power dissipation can also be reduced by having multiple transitions of smaller magnitude as in the multi-step profile proposed in [3] as compared to just one transition of large magnitude as in the select pulse of the conventional line-by-line addressing [5]. We have shown that the power dissipation of a multi-step waveform (dotted lines in Fig. 5) is lower than that of a pulse when the frame frequency or refresh rate is the same. The reduction in power consumption when the pulses in the addressing techniques are replaced by multi-step waveforms having energy that is equal to that of the pulses; in both non-multiplexed and multiplexed LCDs [3] is as follows:

$$\frac{P_{\text{multi-step}}}{P_{\text{pulse}}} = \left(\frac{3(T-T_0)}{3s(T-T_0)-(4s+1)(s-1)T_s}\right). \quad (5)$$

Here, s is the number of steps in the multi-step profile and T_s is the width of the step. It is important to note that the supply voltage of the driver circuit increases by a factor

$$\frac{V_{\text{multi-step}}}{V_{\text{pulse}}} = \frac{V}{V_p} = \sqrt{\frac{T}{T-T_0}\left(\frac{3s(T-T_0)}{3s(T-T_0)-(4s+1)(s-1)T_s}\right)}. \quad (6)$$

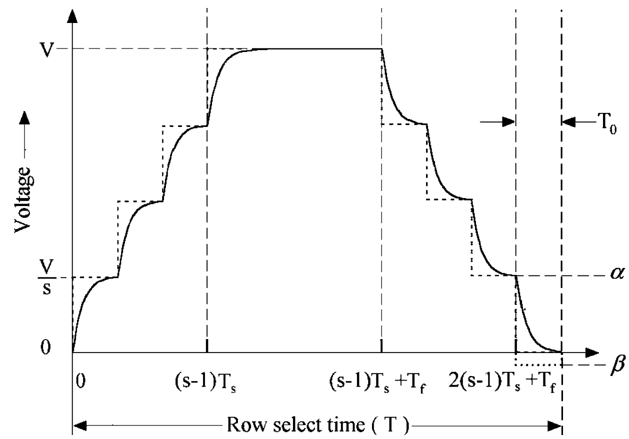

Fig. 5. Multi-step waveform profile with *RC* distortion and $s = 4$. Ideal waveform is shown in dotted lines and it is held at zero during T_0.

Here, V is the peak amplitude of the multi-step waveform that has the same rms voltage across a pixel as that of a single pulse of duration T and amplitude V_p. The expressions in (5) and (6) are valid when s is a positive integer (greater than or equal to 1). The proposed multi-step waveform reduces to the single pulse of the conventional addressing techniques when $s = 1$ and $T_0 = 0$. Consequently the ratios in (5) and (6) reduces to unity for this condition i.e., single pulse of 100% duty cycle. When $s = 1$ and T_0 is nonzero, the multi-step waveform reduces to a single pulse with a duty cycle of $((T-T_0)/T)$. The peak voltage correspondingly increases by a factor $\sqrt{T/(T-T_0)}$ in order to deliver the same energy over duration T. The analysis presented in [3] is based on the assumption that the time constant $(\tau = RC)$ of the drive circuit is small as compared to the step width (T_s). It (T_s) depends on the number of steps (s) in the multi-step waveform, frame refresh frequency (f), T_f duration of the voltage V, and the number of lines that are multiplexed (N) in the display. The time constant (τ) may become comparable to the step width (T_s) with increase in the number of lines multiplexed (N) and the number of steps (s). Then the decrease in the rms voltage across the pixel due to the distortion in the addressing waveforms will no longer be negligible. Effects of *RC* distortion on the rms voltage, power dissipation and the peak voltage in multi-step waveforms are presented in Section V.

V. Analysis of Multi-Step Waveforms With Distortion

Let us consider a multi-step waveform profile of period (T) with distortions (due to a significantly large time constant) shown in Fig. 5 as the select waveform. The ideal waveform profile without any distortion is also shown with dotted lines in Fig. 5. The duration of the ascending and descending steps is chosen to be equal to T_s except for T_f and T_o, the duration of the peak and zero voltage respectively. The waveform profile in Fig. 5 may be split into four distinct intervals:

1) ascending steps of duration T_s;
2) flat region (at top) of duration T_f when the voltage is V;
3) descending steps of duration T_s;
4) duration T_0, when a negative voltage (β) is applied to ensure that the voltage is zero at the end of select time.

The expression for the voltage that is applied to a pixel during an ascending step is given by

$$V_{\text{pixel}}(t) = k\frac{V}{s} - \frac{V}{s}\left(\sum_{j=0}^{k-1} e^{-jT_s/\tau}\right) e^{-(t-T_s(k-1))/\tau}. \quad (7)$$

This expression is valid for the kth $(1 \leq k \leq s-1)$ ascending step in the interval $(k-1)T_s \leq t \leq kT_s$. The first term in (7) represents the excitation corresponding to the kth step while the second term represents the exponential voltage drop across the resistor. Similarly, the expression for descending steps is as follows:

$$V_{\text{pixel}}(t) = \frac{V}{s}\left((s-k) + c_k e^{-(t-T_f-T_s(s+k-2))/\tau}\right) \quad (8)$$

wherein

$$c_k = \left[\left(\sum_{j=0}^{k-1} e^{-jT_s/\tau}\right) - \left(\sum_{j=0}^{s-1} e^{-jT_s/\tau}\right) e^{-(T_s(k-1)+T_f)/\tau}\right]. \quad (9)$$

The expression in (8) is valid for the kth $(1 \leq k \leq s-1)$ descending step when the pixel is discharged to a lower voltage during the interval $((s+k-2)\,T_s + T_f) \leq t \leq ((s+k-1)\,T_s + T_f)$. The voltage across the pixel at the end of the $(s-1)$th descending step say α is obtained by substituting $t = ((s+k-1)\,T_s + T_f)$ and $k = (s-1)$ in (8) i.e.,

$$\alpha = \left(\frac{V}{s}\right)\left[\left(\sum_{j=0}^{s-1} e^{-jT_s/\tau}\right) - \left(\sum_{j=0}^{s-1} e^{-jT_s/\tau}\right) e^{-(T_s(s-1)+T_f)/\tau}\right]. \quad (10)$$

When the time constant is large, the voltage across the pixel (capacitor) may not reach the non-select voltage at the end of T_o resulting in a residual voltage across the pixel at the end of each select time. This residual voltage will alter the rms voltage across the pixel depending on the data voltage for the pixel in the row that is selected next resulting in crosstalk. Hence, pixels that are driven to the same state in different parts of the matrix display will have different rms voltages across them leading to poor brightness uniformity of pixels in the display. In order to maintain good brightness uniformity and avoid cross talk, we propose to apply a negative voltage (β) during the interval T_o, so that it will force the voltage to be zero at the end of T_o (to discharge completely). The negative voltage (β) required to discharge the capacitor to zero within T_o can be computed by solving the charging equation for a capacitor over the interval T_o as

$$V_{\text{pixel}}(T) = 0 = \beta - (\beta - \alpha)\, e^{-(T_0/\tau)}. \quad (11)$$

Simplifying (11) we get

$$\beta = \left(\frac{\alpha}{1 - e^{(T_o/\tau)}}\right). \quad (12)$$

Voltage across the pixel during subsequent time intervals will not depend on the voltage across the pixel during the select time because the voltage is fully discharged at the end of T by applying a voltage of opposite polarity even when the time constant is large. Application of a negative voltage to bring the voltage across the pixel to zero at the end of the select time interval (without affecting the energy delivered during the select time) ensures that the power dissipation due to one pixel does not depend on the states of the neighboring pixels just as the introduction of a short duration of zero voltage across the pixel in [3]. This analysis will be valid even when the time constant is large because the voltage is brought to zero at the end of T. Energy delivered to a pixel during the select time T is computed as follows:

$$E_{RC\text{–distortion}} = \left[\left(\sum_{k=1}^{s-1} E_k\right) + E_s + \left(\sum_{k=1}^{s-1} E'_k\right) + E'_s\right]. \quad (13)$$

Here, the first and third terms correspond to the energy dissipated during the ascending and descending steps; the second and last terms correspond to energy dissipated when the applied voltage is V and β, respectively. Instantaneous voltage across the pixel is squared and integrated within the appropriate limits to obtain the energy dissipated during each time interval. The energy delivered to the pixels will be less than that of the ideal waveform profile due to the distortions in the waveform and the introduction of negative voltage (β). Decrease in the energy delivered to the pixel can be compensated by either:

1) a uniform increase in amplitude of all the steps; or
2) an increase in the amplitude of peak voltage that is applied during T_f; or
3) an increase in the amplitude of just the first step in the select profile.

Effect of increase in amplitude of all the steps (case 1) can be determined analytically; if $\gamma = (E_{pulse}/E_{RC\text{-distortion}})$ then the excitation voltages of all the steps have to be increased by a factor $\sqrt{\gamma}$ to obtain the same energy as that of a pulse of amplitude V_p. Here, the power dissipation also increases by the factor γ. It is not possible to estimate the increase in peak amplitude and power dissipation for other two cases analytically. However, they are estimated numerically. The three methods of correcting the energy in the select profile may be compared using the following criteria: 1) increase in the peak voltage and 2) reduction in power dissipation. Increase in the amplitude of the peak voltage is the least when the amplitude of the first step alone is corrected (case 3); also it has the lowest power dissipation for a wide range of time constants. We have included these corrections in analysis and comparison of power dissipation and supply voltage in this paper.

VI. Results

Power dissipation of the multi-step waveform as compared to the power dissipation of a single pulse (having the same duty cycle) is plotted as a function of the *RC* time constant (τ) in Fig. 6. The durations T_o and T_f are chosen to be $0.1T$ and $2T_s$, respectively. The power dissipation decreases significantly with increase in s when the time constant is small. Saving in power achieved by increasing s is small when the time constant is large. About 30% reduction in power dissipation can be

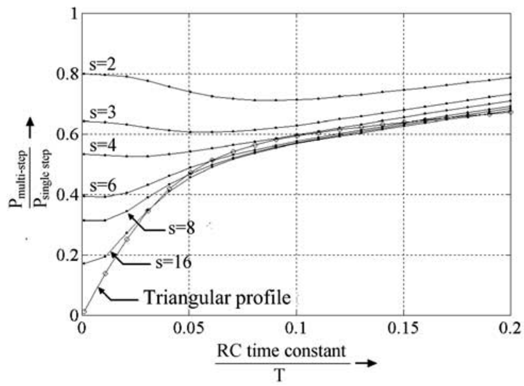

Fig. 6. Power dissipation (normalized to that of a single pulse) versus normalized time constant for different values of s; $T_o = 0.1T$ and $T_f = 2T_s$.

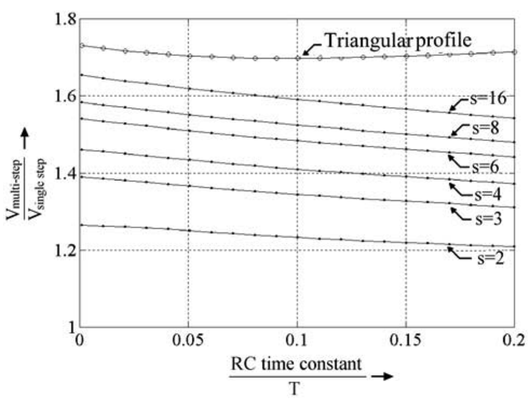

Fig. 7. Peak voltage (normalized to that of a single pulse) versus normalized time constant for different values of s; $T_o = 0.1T$ and $T_f = 2T_s$.

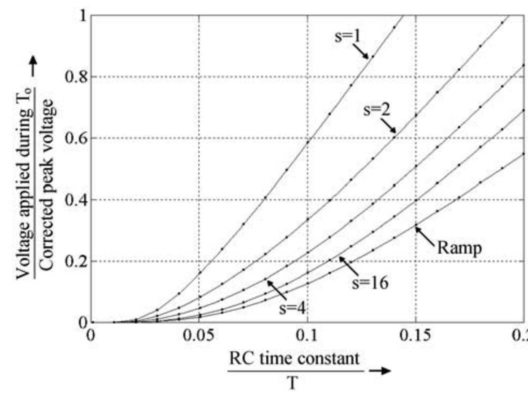

Fig. 8. Magnitude of voltage to be applied during T_o (normalized to the corrected peak voltage) as a function of normalized time constant; $T_o = 0.1T$ and $T_f = 2T_s$. This voltage is necessary to ensure that the voltage is equal to the non-select voltage at the end of select time.

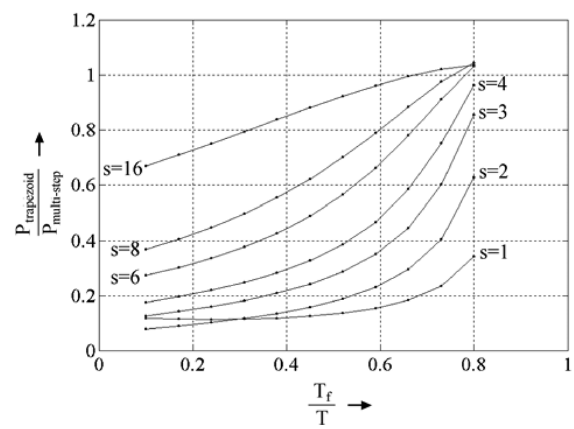

Fig. 9. Ratio of power dissipation of the trapezoidal waveform to that of the multi-step waveform as a function of T_f for different values of s; $T_o = 0.1T$ and $\tau = 0.01T$.

achieved with just three steps when $\tau = 0.2T$. The multi-step profile tend towards a triangular waveform when the number of steps is greater than 3 and $T_f = 2T_s$. Power dissipation of the triangular waveform is also plotted in Fig. 6 for comparison. The triangular waveform has the lowest power dissipation, especially for small values of τ. However, it is achieved with a 70% increase in the peak voltage. Fig. 7 compares the supply voltage of the multi-step waveform with that of a single pulse for various values of τ and s. It is evident from the plots in Figs. 6 and 7 that at lower values of time constant τ, a large reduction in power can be achieved with higher values of s and consequently a higher supply voltage. However, it may be adequate to choose a small value of s because it is possible to achieve reasonable reduction in power with a moderate increase in supply voltage when τ is large. Amplitude of the voltage (β) that is applied during T_o to ensure that the voltage is equal to the non-select voltage at the end of select time is plotted in Fig. 8 as a function of the time constant τ. It is normalized to the peak voltage for the corresponding number of steps (s). As the number of steps is increased, the multi-step waveforms tend towards triangular or trapezoidal profiles. They have a gradual change in amplitude and do not have any abrupt changes that are responsible for high power dissipation. Amplitude of β is comparable to the peak voltage when τ is large. Most of the addressing techniques, especially multi-line techniques have both positive and negative voltages and hence the supply voltage of the driver circuit will not double in such cases. Power dissipation of the trapezoidal waveform as compared to that of a multi-step waveform is plotted in Fig. 9 as a function of T_f i.e., the duration of the peak voltage. However, we have ensured that the value of T_f is the same (for proper comparisons) for both the multi-step and trapezoid waveform profiles when the ratio is computed in the plot in Fig. 9. Plots for several values of s (the number of steps) are shown assuming $T_o = 0.1T$ and $\tau = 0.01T$. It is clearly seen that the trapezoidal waveform offers a saving in power when compared to multi-step waveforms for different values of s. Figs. 10 and 11 compare the power dissipation and peak voltage of the trapezoidal waveform with multi-step waveforms as a function of the time constant (τ). Both trapezoidal and multi-step profiles have a fixed value of T_f i.e., $T_f = 0.3T$ as compared to Figs. 6 and 7, respectively, wherein T_f is a function of T_s. The power dissipation plot i.e., Fig. 10 shows a similar trend but the magnitude of power saving differs especially for the multi-step waveforms. Values of s for which the condition $T_f = 0.3T$ represents an increase in T_f as compared to $T_f = 2T_s$ show a larger saving in power as compared to the plots in Fig. 5. Fig. 11 compares the peak amplitude of the trapezoidal waveform with that of the multi-step waveform for

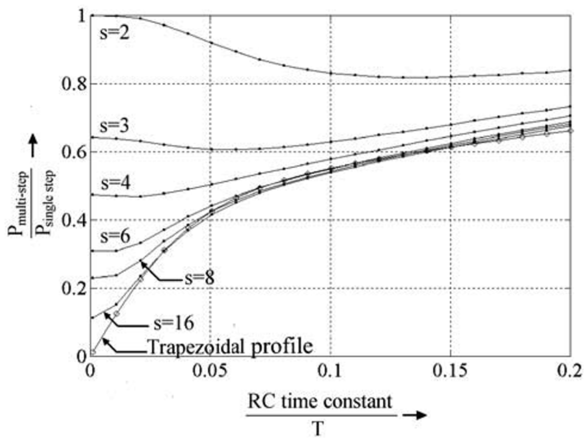

Fig. 10. Power dissipation as a function of τ for different values of s; $T_o = 0.1T$ and $T_f = 0.3T$.

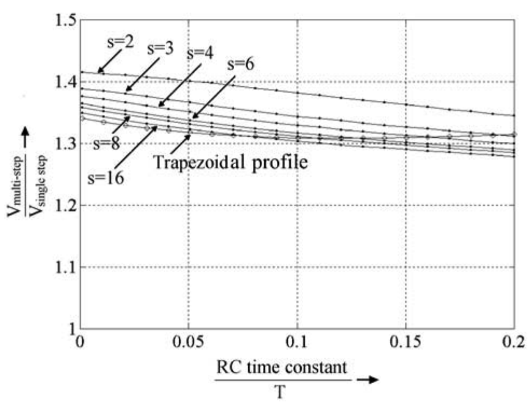

Fig. 11. Peak voltage as a function of normalized time constant for different values of s; $T_o = 0.1T$ and $T_f = 0.3T$.

several values of s. Variation in peak voltage is less here as compared to that in Fig. 5 because T_f is constant. Thus the duration of the peak voltage T_f can be chosen to control the supply voltage of the driver circuit. Although the power dissipation decreases with increase in the number of steps, it follows the law of diminishing returns and the supply voltage also increases with s. A moderate value of s ensures that there is reduction in power dissipation with a low supply voltage. The analysis of power dissipation with the proposed new select profiles can be extended to matrix addressing techniques and the reduction in power or the increase in supply voltage will be the same as that of the select voltage profile i.e., the result of this analysis is independent of the addressing technique as shown in [3]. All that needs to be done is to replace the select pulses in an addressing technique with one of the select profiles proposed in this paper. Typical addressing waveforms of the line-by-line addressing technique [5] using trapezoidal select waveforms are shown in Fig. 12.

VII. Implementation

The select waveforms can be generated easily and it can be incorporated in to the driver circuit of any addressing technique without much increase in the hardware complexity for the following reasons.

1) The triangular and trapezoidal waveform can be generated using op-amp circuit and its output can be used to modulate the voltage across the voltage level generator (resistor network) in the display.
2) The voltage across the voltage level generator can be switched to generate the multi-step voltage profile using a few transistors [3].
3) The output of the voltage generator circuit can be directly fed to the inputs of the standard drivers (like 44100) and the hardware complexity of both the row and column drivers is same as that of addressing techniques with a select pulse with an abrupt transition of large magnitude.

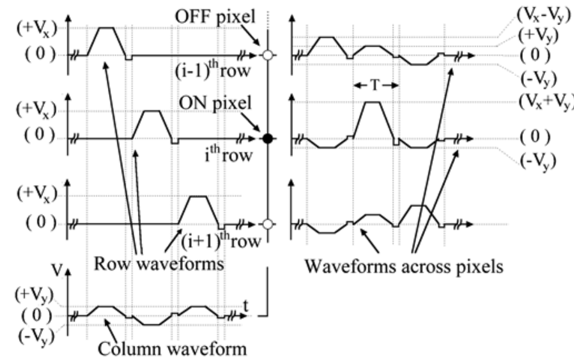

Fig. 12. Typical addressing waveforms when trapezoidal profile is introduced in line-by-line addressing.

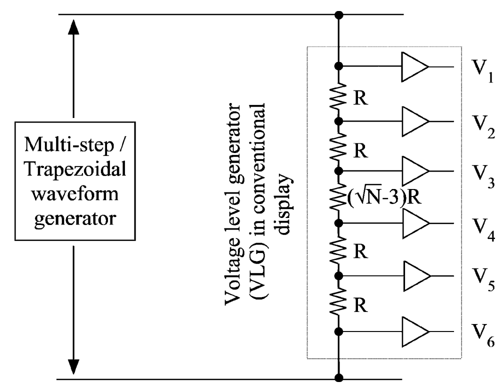

Fig. 13. Modified VLG for practical implementation.

A minor modification to the driver circuit is adequate to implement the proposed scheme as illustrated in Fig. 13. The figure shows the voltage level generator (VLG) for conventional line-by-line addressing. The voltage across the VLG is modulated with the desired select waveform profile i.e., a trapezoidal or triangular or multi-step waveform, instead of a fixed voltage as in the conventional addressing techniques. The outputs of the VLG: V_1 to V_6 viz., the select, non-select and data voltages will also have the same waveform profile as the excitation and they are fed to V_1 to V_6 inputs of row and column drivers. In summary, the increase in hardware complexity of the drive circuit is not high because the additional circuit is common to the entire set of driver integrated circuits in the display; the voltage profiles can be generated using either a few resistors and multiplexers [3] or some simple circuit using operational amplifiers. Distortions in the addressing waveforms will be independent of the information that is displayed when the select waveform profile is forced to non-select voltage at the end of select period by applying a correction voltage β during the period T_o. The introduction of β does not significantly alter the hardware complexity of the proposed solution except for the amplitude of the waveforms. The voltage β can be generated with two additional resistors in the potential divider of the VLG. Supply voltage of the driver circuit will increase if β is grater than V_c and the increase will be proportional to the difference of β and V_c. Thus, good brightness uniformity (among pixels that are driven to the same state) may be achieved as a spin-off out of our effort to reduce the power consumption in the display with simple modification to the VLG in the driver circuit that will not increase the hardware complexity as well as the cost of the drive circuit.

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