Low Power Techniques for Gray Shades in Liquid Crystal Displays

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***Abstract*—The largest transition in the select waveform of successive approximation technique is eliminated to reduce power dissipation in liquid crystal displays. Power dissipation in the driver circuit is analyzed for gray scale images by considering three select sequences. They are compared and a new select sequence is proposed to achieve low power dissipation. An additional pulse is introduced in the select waveform to reduce peak amplitude of select and data waveforms to achieve a low supply voltage for the driver circuit.**

***Index Terms*—Addressing, gray shades, liquid crystal displays (LCDs), low power, matrix displays, multiplexing, scanning.**

I. Introduction

FLAT panel displays, viz. liquid crystal displays (LCDs), electro luminescent (EL), and plasma display panels (PDPs) have capacitive type pixels; and they are modeled as a two-dimensional array with capacitors that are located at the intersection of row and column address lines. Power is dissipated in the driver circuit when pixels are charged and discharged to voltages that are determined by addressing waveforms. It is a major component of power consumption in these displays. Multi-step waveforms were proposed to reduce power dissipation in LCD [1]. Several waveforms, viz. triangular, trapezoidal, as well as their discrete versions, with multi-steps [2] can be used to reduce power dissipation in driver circuit of bilevel displays wherein pixels are driven to either ON or OFF states. The main objective of the work is to reduce power dissipation in LCDs for images with gray shades. Of the several techniques to display gray shades in LCDs, successive approximation techniques [3], [4] and wavelet-based techniques [5], [6] require less hardware to display a large number of gray shades and it is possible to reduce power dissipation of these techniques as described in this paper. Successive approximation technique that selects one address line at a time (SAT-L1) [4] is well suited for low power applications. SAT-L1 can display 2^g gray shades in g time intervals as compared to (2^g-1) time intervals that are necessary in case of pulsewidth modulation [7] and frame rate control [8]. The number of voltages in the column (data) waveforms of SAT-L1 is small $(2.g)$ for displaying 2^g gray shades as compared $2^{(g+1)}$ voltages in waveforms of the pulse amplitude modulation [9]. Selection ratio (ratio of RMS voltage across ON pixels to that across OFF pixels) of SAT is the maximum as compared to the row pulse height modulation [10]. Hardware complexity of drivers is the lowest for SAT-L1. Drivers that are capable of applying one out of two voltages are adequate to display gray shades with SAT-L1. A method to reduce power dissipation and supply voltage of SAT-L1 is proposed in this paper. A similar approach can be adapted to reduce power dissipation of addressing techniques with multiple select pulses viz., successive approximation based on multi-line addressing techniques and wavelets-based techniques. SAT-L1 is reviewed briefly in the next section.

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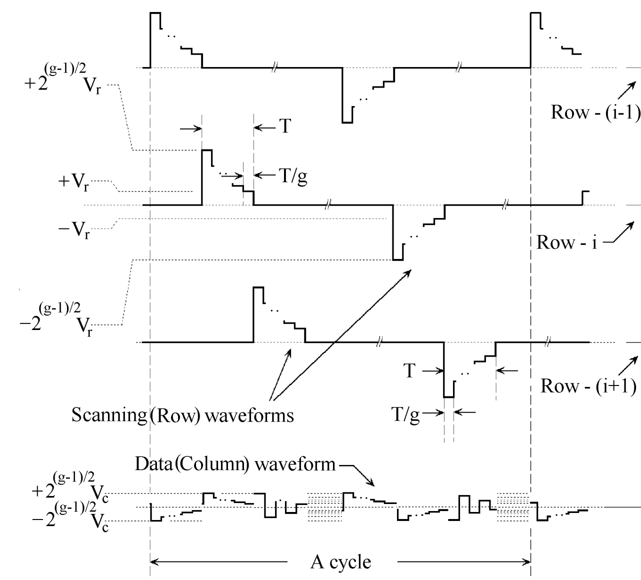


Fig. 1. Addressing waveforms of successive approximation technique that is based on selecting one address line at a time (SAT-L1).

II. Successive Approximation Technique Based on Line-by-Line Addressing (SAT-L1)

Address lines (either rows or columns) in a matrix display are selected sequentially each with 'g' pulses (of different amplitudes) during a period T, as shown in Fig. 1. Here, T is the select time of an address line and g is the number of bits that is used to represent gray shades of pixels. Amplitude of select pulses is proportional to weight of gray shade bits. Let V_r be the amplitude of the select pulse that corresponds to the least significant bit (LSB). Amplitude of the select pulse is increased by a factor $\sqrt{2}$ for each higher bit. The maximum amplitude of select pulses viz. $(2^{(g-1)/2}V_r)$ corresponds to the most significant bit (MSB). Address lines (say rows) are selected with a pulse of amplitude $2^{(g-1)/2}V_r$ for the duration $(T-T_0)/g$ and rest of the address lines are grounded. A data voltage of $+2^{(g-1)/2}V_c$ is applied to column of the matrix display, if MSB of the pixel located in that column is 'logic-0' and a data voltage of $-2^{(g-1)/2}V_c$ is applied to a column if MSB of the pixel is 'logic-1.' In general, if an address line is selected with a voltage $(2^{k/2}V_r)$ corresponding to the bit-k during a time interval, then amplitude of data voltages will be proportional to $(2^{k/2})$ where as the sign of data voltage will be same as the select pulse if bit-k is logic-0 and opposite to that of select pulse if the bit-k is logic-1. The display is refreshed continuously by selecting each address line with g-select pulses corresponding to the gray shade bits and the N-address lines are sequentially selected with 'g' select pulses, as shown in Fig. 1. Polarity of the select pulses is periodically reversed to ensure DC free waveforms across the pixels. This technique achieves the maximum selection ratio (defined as the ratio of RMS voltage across the ON pixels to that across the OFF pixels) as described in [4]. Principle of reducing power dissipation is described next.

III. Principle

Addressing waveforms of LCD are not unique because the root mean square (RMS) voltage across the pixel determines its state and it is possible to achieve the desired RMS voltage across pixels with several addressing techniques [3]–[10]. Shape of the addressing waveforms is important to reduce power consumption as in the case of a *RC*-circuit with a resistor and a capacitor in series; wherein a slowly varying ramp waveform to charge (or discharge) a capacitor will minimize the power dissipated in the resistor. Power dissipation is proportional to square of the step voltage and it is preferable to avoid large transitions in the addressing waveforms. Almost all the addressing techniques for driving LCD are based on pulses (to select address lines) with abrupt transitions and replacing 'pulses' with 'triangular waveforms' can minimize power dissipation. A 50% reduction in power dissipation can be achieved when pixels are charged or discharged in two steps with a staircase waveform having equal steps of amplitude $(V/2)$ instead of a single step of amplitude V [11]. Order of application (sequence) of select pulses is not important for displaying gray shades because the RMS voltage is independent of it. However, the power dissipated in drivers will depend on the sequence because the step size of transitions will be different for different sequences. The transition from $\pm 2^{(g-1)/2}V_r$ to 0 in select waveforms and the transition from $\pm 2^{(g-1)/2}V_c$ to 0 in data waveforms of SAT-L1 (shown in Fig. 1) are the major contributors to power dissipation in the driver circuit. For example, about 63%–85% (for $g = 2$ to 8) of power dissipated when a capacitor is charged to a voltage $2^{(g-1)/2}V$ and rest of the power is dissipated when the capacitor is discharged with g-steps where in the voltage is reduced by a factor $(1/\sqrt{2})$ during each transition. There is considerable scope to reduce power by decreasing the amplitude of transitions as evident from this example. Some select sequences are considered in the next section.

IV. Select Sequences to Reduce Power Dissipation

Three sequences of select pulses are considered and they are evaluated for their potential to reduce power dissipation in *RC*-circuit before introducing them in to the addressing techniques.

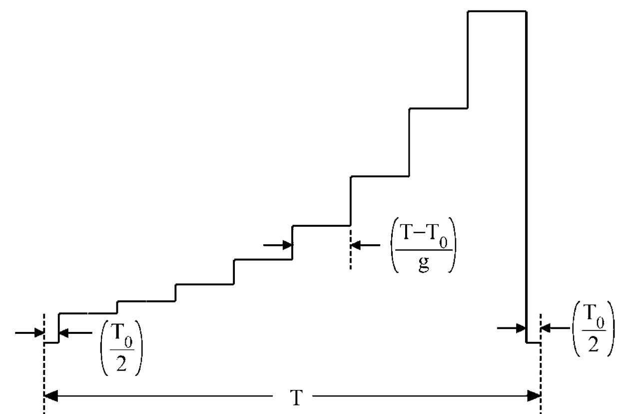


Fig. 2. 'Select sequence-a' that is held at non-select voltage during $(T_0/2)$ and the first step has unit amplitude. Amplitude of select pulses is increased by a factor $\sqrt{2}$ for each bit starting from least significant bit (LSB) to the most significant bit (MSB). It is followed by an abrupt transition to zero and it is held at zero during $(T_0/2)$ at the end of the select time T of an address line.

A. Select Sequence-a

Select pulses are arranged in ascending order; starting from a pulse of unit amplitude that corresponds to the LSB (amplitude of the select pulse is normalized to that of LSB) and amplitude of each successive pulse is increased by a factor-a during the transition. The final select pulse of amplitude $a^{(g-1)}$ corresponds to the MSB and the final transition from $a^{(g-1)}$ to zero is the largest transition in the select waveform. This sequence, shown in Fig. 2, is considered as the reference sequence to compare other sequences that are proposed in this paper and it is referred to as 'select sequence-a'. Power dissipated in the series resistor of an *RC*-circuit is proportional to

$$p(a) \propto \left[1 + \sum_{k=1}^{n} \left(a^k - a^{(k-1)}\right)^2 + a^{2n}\right]. \quad (1)$$

Here, the first term corresponds to 0 to 1 transition, the summation in the second term corresponds to transitions from the select pulse of LSB to the final pulse corresponding to the MSB and the last term corresponds to transition from voltage corresponding to MSB to 0 (non-select voltage). The expression in (1) simplifies to

$$p(a) \propto \frac{2 \cdot a^{(2n+1)} + 2}{(a+1)}. \quad (2)$$

Power dissipated in the series resistance of RC-circuit, when the capacitor is charged with 'g' select pulses and discharged to zero is obtained by substituting '$(g-1)$' for 'n' because $k = 1$ corresponds to the second transition from 1 to a^1, as shown here.

$$p(a) \propto \frac{2 \cdot a^{2g-1} + 2}{a+1} \quad \because n = g - 1. \quad (3)$$

Select pulses may also be arranged in descending order as in waveforms of the SAT-L1 in Fig. 1 and select sequence of SAT-L1 in Fig. 1 is equivalent to that in Fig. 2 from the point of power dissipation because the amplitude of transitions and the number of transitions are same for both the sequences.

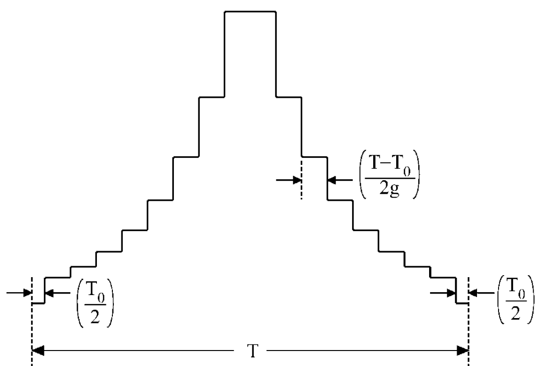


Fig. 3. Select sequence with ascending and descending select voltages to eliminate the largest transition in 'sequence-a'. Number of transitions is about twice that of 'sequence-a'.

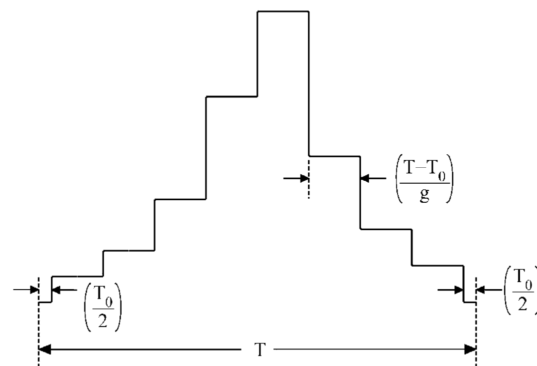


Fig. 4. New select sequence that has the same number of transitions as that of 'sequence-a' is shown. The largest transition in 'profile-a' is eliminated but amplitude of other transitions increases by a factor 'a' ($\sqrt{2}$).

B. Select Sequence-b

The largest transition in 'sequence-a' can be eliminated by concatenating 'g' select pulses corresponding to MSB to LSB in descending order to the select pulses (in ascending order) of Fig. 2 as shown in Fig. 3. Hence, the number of transitions in the resulting sequence 'select sequence-b' is almost double that of the 'select sequence-a'. It has $2g$ transitions as compared to $(g+1)$ transitions of 'sequence-a'. The display can be addressed with the 'sequence-b' however, the duration of select pulses will be about half that of 'sequence-a' except for the pulse corresponding to MSB; if duration of select time of address lines T is same as that of sequence to ensure that the display is refreshed at the same rate in both the cases. The first and last pulses of 'sequence-b' correspond to LSB and the peak voltage of waveform in Fig. 3 corresponds to MSB. The peak voltage is proportional to $a^{(g-1)}$ and it is wider as compared to other voltages. Amplitude of select pulses is reduced by a factor a^{-1} to obtain the descending part of the select waveform. Power dissipated in the series resistor, when the capacitor in *RC*-circuit is charged and discharged with waveform of 'sequence-b' is given by

$$p(b) \propto 2\left(1 + \sum_{k=1}^{n}(a^k - a^{k-1})^2\right). \tag{4}$$

The first term corresponds to transition from 0 to 1 and from 1 to 0 and the summation in the second term corresponds to rest of the transitions

$$p(b) \propto \frac{2 \cdot a^{2n}(a-1)+4}{(a+1)}. \tag{5}$$

Here again, $n = (g-1)$ corresponds to the transition to (or from) the select voltage corresponding to MSB from (to) the next significant bit and the simplified expression for the power dissipation in a resistor of an *RC*-circuit is

$$p(b) \propto \frac{2 \cdot a^{2(g-1)}(a-1)+4}{(a+1)}. \tag{6}$$

Power dissipation of 'sequence-b' is compared with that of the select 'sequence-a' by taking the ratio of the expression in (6) to the expression in (3) and by assigning $a = \sqrt{2}$ as in the case of successive approximation techniques [3], [4]

$$\frac{p(b)}{p(a)} = \frac{2^g(2-\sqrt{2})+4\sqrt{2}}{2(2^g+\sqrt{2})}. \tag{7}$$

Power dissipation of sequence-b is about 70% of 'sequence-a ' when $\mathrm{g} = 2$, and it asymptotically reaches to about 30% for higher values of 'g' ($g > 8$).

Although the 'sequence-b' has the potential to reduce power dissipation, it has double the number of transitions as compared 'sequence-a'. It is preferable to have less number of transitions in addressing waveforms to achieve good brightness uniformity of pixels for the following reasons:

1) RMS voltage across pixels reduces due to distortion of pulses in the addressing waveforms and the difference between ideal and actual RMS voltages increases with the number of transitions when the frame frequency is a constant;
2) frequency spectrum of waveforms across pixels will shift towards higher frequencies as the number of transitions is increased. Some high frequency components may be greater than the crossover frequency of dielectric relaxation of liquid crystal mixture in the display and the effective RMS voltage across pixels will be reduced.

Hence, poor brightness uniformity among pixels that are driven to same gray shade is due to transitions and select sequences with less number of transitions can minimize the nonuniformity.

C. Select Sequence-c

The select 'sequence-c' that is shown in Fig. 4 has the same number of transitions as that of 'sequence-a' and yet it eliminates the largest transition in 'sequence-a'. A select sequence with ascending as well as descending steps is achieved by arranging select pulses corresponding to alternate bits to appear adjacent to each other and therefore have both ascending as well as descending order with just 'g' pulses as shown in Fig. 4. Step size of ascending steps is a^2 as compared to 'a' of sequence-a' and 'sequence-b'. Similarly, the amplitude is reduced in steps of a^{-2} in the descending steps as compared to a^{-1} in 'sequence-b'.

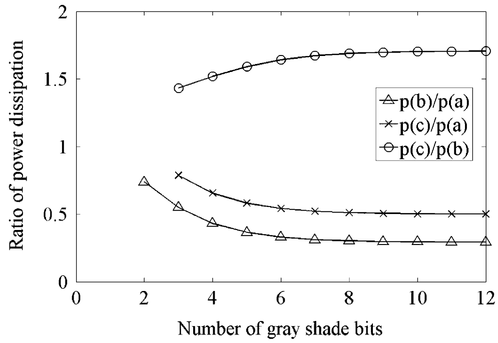


Fig. 5. Plots that compare power dissipation in the series resistance of *RC*-an circuit during the period T when the capacitor is charged and discharged with the capacitor with the three select sequences.

Power dissipated in *RC*-circuit when the 'sequence-c' is used to charge and discharge a capacitor is as follows:

$$p(c) \propto \left[1 + a^2 + (a^n - a^{(n-1)})^2 + \sum_{k=2}^{n} (a^k - a^{(k-2)})^2\right]. \tag{8}$$

Here, the first term corresponds to the unit step, the second term corresponds to the final transition from a to zero, the third term corresponds to the transition 'from' or 'to' the peak voltage 'to' or 'from' an adjacent pulse of lower amplitude, and the summation in the last term corresponds to the transitions with step size of either a^2 or a^{-2}. It simplifies to the expression in (9) and it can further be compared with 'sequence-a' by the ratio in (10) after substituting $\sqrt{2}$ for the step size a

$$p(c) \propto 2 \cdot (a-1).a^{(2g-3)} - a^2 + 2 \tag{9}$$

$$\frac{p(c)}{p(a)} = \frac{2^g + 2\sqrt{2}(\sqrt{2}+1)}{2(2^g + \sqrt{2})}. \tag{10}$$

Power dissipation in the *RC*-circuit with 'sequence-c' is less as compared to that of 'sequence-a'; it is about 79% of 'sequence-a' for $g = 3$ and it asymptotically approaches 50% when g is greater than 8, as shown in Fig. 5. However, it is more than that of 'sequence-b' as shown by the plot of ratio $p(c)/p(b)$ in the figure. Analysis and comparison of power dissipation when these sequences are used to drive matrix display is presented in the next section.

V. Analysis of Power Consumption

A matrix-type LCD is modeled as a two-dimensional array of capacitors. Liquid crystal mixtures exhibit dielectric anisotropy; the effective dielectric constant depends on the molecular orientation with reference to the electric field because the dielectric constants that is measured parallel and perpendicular to the long axis of rod-like liquid crystal molecules are not equal. Hence, the pixels are equivalent to voltage dependent capacitors because the orientation of the molecules depends on the voltage across the pixel. In twisted nematic (TN) and super-TN (STN) liquid crystal displays, the capacitance of a pixel that is ON $(C_{\rm ON})$ can be higher by a factor of two or more than the capacitance of same pixel in OFF state $(C_{\rm OFF})$. Capacitance of

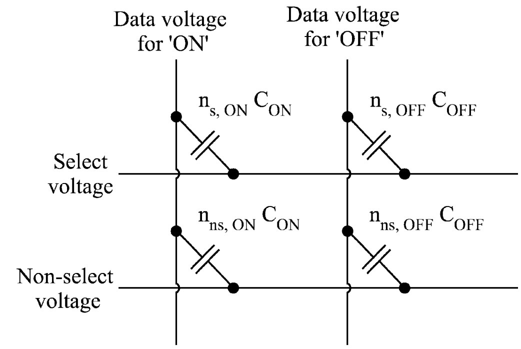


Fig. 6. Equivalent circuit of a matrix-type LCD at a given instant of time, the number of ON and OFF pixels in the selected and non-selected rows depends on the row that is selected as well as the image.

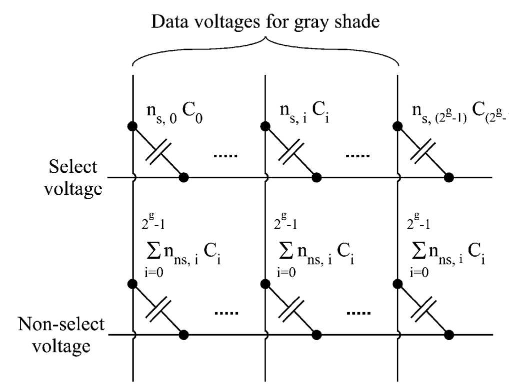


Fig. 7. Equivalent circuit of a matrix display during a select time when the data voltages correspond to the gray shades.

the pixels that are driven to some intermediate gray shade will be within the capacitance of the two extreme states (ON and OFF). Hence, the power dissipation in a matrix LCD depends on the actual image and prior knowledge of the image is necessary to compute the power dissipated in the driver circuit through analysis.

However, it is not necessary to know the image for comparing different waveforms because we can take the ratio by assuming that image is same for both the cases. The equivalent circuit of a matrix display when select and data voltages are applied during a short period $(T - T_0)/g$ is given in Fig. 6. Here $n_{s,\rm ON}$ is the number of pixels that are driven to ON state in a selected row, $n_{s,\rm OFF}$ is the number of OFF pixels in the selected row, $n_{ns,\rm ON}$ is the number of ON pixels in non-selected rows, and $n_{ns,\rm OFF}$ is the number of OFF pixels in the non-selected rows. Both the select and data waveforms have similar transitions (except for polarity of the data waveforms) in a bilevel display and therefore the reduction or increase in power dissipation is same as in the case of simple *RC*-circuit [1] as compared in Fig. 5. The equivalent circuit of a matrix LCD during a select time is relatively more complex when gray shades are displayed, as shown in Fig. 7. Here, $n_{s,i}$ is the number of pixels in the selected row that are being driven to the gray shade 'i' and similarly $n_{ns,i}$ is the number of pixels in the non-selected rows that are driven to the gray shade 'i'. However, the pixels in the non-selected rows will get voltages corresponding to the state of the pixels in the selected row and therefore pixels in non-selected rows are grouped into 2^g columns depending on column voltages that correspond to 2^g gray shades. Capacitance of pixels in non-selected rows add up and amplitude of transitions across them is relatively small because just the data voltages appear across them as compared to the large transitions across the pixels in selected rows but the capacitances are small as compared to that in non-selected rows. Relative merits of select profiles are estimated with the following assumptions.

1) Capacitance of pixels does not follow the abrupt changes in addressing waveforms because liquid crystal molecules take time to reorient themselves to the electric field.
2) Period of the addressing waveform is small as compared to the response times.
3) RMS voltage across the pixel is same for a gray shade irrespective of the profile of select pulses and therefore capacitance of the pixel depends on its gray shade.
4) Capacitance of all pixels is assumed equal to simplify the analysis although the capacitance depends on gray shade of the pixel. An average value can be assumed by considering the fact that capacitances of pixels that are driven to the same gray shade add up and similarly capacitances of pixels in non-selected rows add up because they are parallel to each other.
5) Probability of occurrence of all the gray shades in the image is assumed to be equal, to obtain a closed form expressions for power dissipation.

These assumptions are valid because liquid crystal molecules are slow to follow and orient themselves to the time-varying voltages of the addressing waveforms and response times are usually larger than the period of a cycle. Although, not all gray shades may be equally probable in small regions of an image and to a lesser extent over large images, it gives an estimate of power dissipation when there is no prior knowledge of the image. It is important to note that the transitions across the pixels in non-selected rows will depend on the gray shades of pixels in the two rows that are selected one after other successively. All possible transitions in the data voltages are equally probable when we assume that the gray shades are equally probable and we can get closed-form expression for power dissipation. Our objective is to compare the power dissipation of different sequences of select pulses by taking ratios and therefore it is not necessary to know the capacitances of pixels. Relative efficiency of select sequences is obtained after ensuring that the RMS voltages are equal for all the select sequences by proper choice of amplitude of select pulses.

Let us consider a voltage transition from a^iV_r to a^jV_r in the select waveform in a matrix display with N rows and M columns. The corresponding transition in data voltages can be any one of the four possibilities depending on the gray scale data of the pixel; viz. $+a^iV_c$ to $+a^jV_c$, $+a^iV_c$ to $-a^jV_c$, $-a^iV_c$ to $+a^jV_c$ and $-a^iV_c$ to $-a^jV_c$. All these are equally probable because the distribution of gray shade is assumed to be uniform. Hence, the power dissipated in the pixels during the select time will be proportional to the expression in

$$p_{i\text{–}j\_\text{select}} \propto \left\{ \begin{array}{l} \left(a^j(V_r+V_c)-a^i(V_r+V_c)\right)^2+\left(a^j(V_r-V_c)-a^i(V_r+V_c)\right)^2 \\ +\left(a^j(V_r+V_c)-a^i(V_r-V_c)\right)^2+\left(a^j(V_r-V_c)-a^i(V_r-V_c)\right)^2 \end{array} \right\}. \quad (11)$$

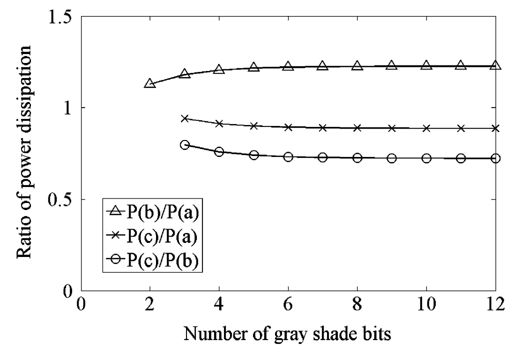


Fig. 8. Comparison of power dissipation when select voltage sequences a-c is used in addressing waveforms. The sequence-c is better than sequence-b because sequence-b has double the number of transitions as compared to sequence-c.

The expression in (11) simplifies to

$$p_{i-j\_\text{select}} \propto 4V_r^2(a^j-a^i)^2+4V_c^2(a^{2.i}+a^{2.j}) \quad (12)$$

Similarly, the power dissipation across pixels during the non-selected time intervals will be proportional to

$$p_{i-j\_\text{non-select}} \propto \left\{ \begin{array}{c} (a^j-a^i)^2V_c^2+(a^j+a^i)^2V_c^2 \\ +(-a^j-a^i)^2V_c^2+(-a^j+a^i)^2V_c^2 \end{array} \right\}. \quad (13)$$

Expression (13) can also be obtained by substituting '0' for V_r in (12) and it simplifies to the following expression:

$$p_{i-j\_\text{non-select}} \propto 4V_c^2(a^{2.i}+a^{2.j}). \quad (14)$$

Power dissipated in a matrix LCD (with N rows) when the select voltage transits from iV_r to jV_r during a scan is

$$p_{i-j\_\text{scan}} \propto (a^j-a^i)^2V_r^2+N(a^{2.i}+a^{2.j})V_c^2. \quad (15)$$

Average power dissipated under the assumption of uniform distribution of gray shades is proportional to

$$P \propto \sum_{\forall \text{ all } a^i \to a^j} \left((a^j-a^i)^2V_r^2+(a^{2.i}+a^{2.j})NV_c^2\right). \quad (16)$$

It is clear from the above expression that reduction in average power dissipation depends on magnitude as well as the order in which select pulses appear in the waveform (sequence) and the magnitude of data voltages. However, it does not depend on the order in which the data voltages appear because we have assumed a uniform distribution of gray shades and, therefore, data waveforms will have equal number of positive and negative transitions from each data voltage to another. However, power dissipation due to transitions in the data waveforms is independent of sequence of the select voltages but it will depend on the sequence of transitions in the scanning waveform. Power dissipated when the select sequences: $a, b,$ and c are used as the row waveform is analyzed in the following equations [see (17)–(22)] at the top of the next page: sequence-a shown in Fig. 2 is considered first.

$$P_{\text{select\_seq}(a)} \propto \begin{bmatrix} V_r^2\left(1+a^{2.(g-1)}+\sum_{k=1}^{g-1}\left(a^k-a^{(k-1)}\right)^2\right) \\ +NV_c^2\left(1+a^{2.(g-1)}+\sum_{k=1}^{g-1}a^{2.k}+a^{2.(k-1)}\right)\end{bmatrix} \tag{17}$$

$$P_{\text{select\_seq}(a)} \propto N\left((4-\sqrt{2}).2^g+2\sqrt{2}-4\right)V_c^2 \tag{18}$$

$$P_{\text{select\_seq}(b)} \propto 2\begin{bmatrix} V_r^2\left(1+\sum_{k=1}^{g-1}\left(a^k-a^{(k-1)}\right)^2\right) \\ +N.V_c^2\left(1+\sum_{k=1}^{g-1}a^{2k}+a^{2(k-1)}\right)\end{bmatrix} \tag{19}$$

$$P_{\text{select\_seq}(b)} \propto N\left((3-\sqrt{2}).2^{(g+1)}+4\sqrt{2}-8\right)V_c^2 \tag{20}$$

$$P_{\text{select\_seq}(c)} \propto \begin{bmatrix} V_r^2\left(1+a^2+\left(a^{(g-1)}-a^{(g-2)}\right)^2+\sum_{k=2}^{g-1}\left(a^k-a^{(k-2)}\right)^2\right) \\ +NV_c^2\left(1+a^2+a^{2(g-1)}+a^{2(g-2)}+\sum_{k=2}^{g-1}a^{2.k}+a^{2.(k-1)}\right)\end{bmatrix} \tag{21}$$

$$P_{\text{select\_seq}(c)} \propto N2^g\left[3-\frac{\sqrt{2}}{2}\right]V_c^2. \tag{22}$$

The unit step of column voltage V_c that corresponds to LSB in the successive approximation technique with duty cycle (select voltage held at non-select voltage during a period T_0 in the select time of T) is given in the following equation.

$$V_c=\sqrt{\frac{T}{T-T_0}}\cdot\sqrt{\frac{g}{2^g-1}}\cdot\left(\sqrt{\frac{N}{2(N-\sqrt{N})}}\right)\cdot V_{\text{th}} \tag{23}$$

Here, T_0 is the time within T (one row select period), during which both the row and column voltages are brought to common potential to ensure brightness uniformity and Vth is the threshold voltage of the electro-optic characteristics of the display. It is considered equal for the above three waveform sequences because pulsewidths of all three are the same. The average power dissipation of the multiplexed waveforms w ith select sequences is compared in Fig. 8. 'Sequence-c' is better than 'sequence-b' to reduce power dissipation when gray shades are displayed in a matrix display when we assume that the entire (2^g) gray shades are equally probable. It is in contrast to that of both the simple RC-circuit and that of matrix displays where in 'sequence-b' is better than 'sequence-c' for the following reasons.

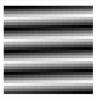
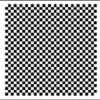
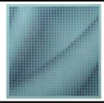
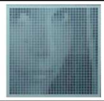
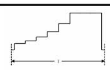
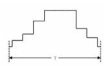
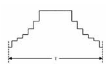
Magnitude of transition during select time is always less than the magnitude of select pulse when the pixels are driven to OFF state. However, when gray shades are displayed power dissipation during select time is high for some of the gray shades. For example, the gray shades: 010101... OR 101010... (i.e., when alternate gray shade bits are not same) introduce large swing across the pixels during select time as compared to the case when neighboring gray shades are the same as in OFF or ON pixels.

Supply voltage of the driver circuit is reduced by decreasing the amplitude of the select pulse corresponding to MSB by a factor $(1/\sqrt{2})$ and the width is doubled so that its amplitude is same as that of the next significant bit. Let us consider a pulse of duty cycle T_p/T then the RMS voltage is $\sqrt{1/T\int_0^{T_p}V^2dt}=V\sqrt{T_p/T}$. If we are interested to reduce the amplitude of the pulse by a factor $(1/\sqrt{2})$ and still want to retain the RMS voltage then it can be achieved by increasing the pulsewidth to $2\cdot T_p$ so that $\sqrt{1/T\int_0^{2\cdot T_p}(V/\sqrt{2})^2dt}=V\sqrt{T_p/T}$. Hence, when the voltage corresponding MSB is reduced an additional pulse is introduced and these two pulses along with the pulse of the next significant bit form a flat top of width 3 as in Fig. 10. Amplitude of the select pulses will increase by a factor $\sqrt{(g+1)/g}$ due to the fact that the select time of a row is left intact so that the frame refresh rate remains the same even after modifying the waveform. Hence, the supply voltage is reduced to $\sqrt{(g+1)/(2g)}$ of supply voltage before the modification of waveform. A 25% reduction in supply voltage is achieved by reducing the amplitude of the select pulse corresponding to MSB; when the number of bits is eight. Power dissipation will be approximately equal to that of $(g-1)$ bits when the supply voltage is decreased by a factor $\sqrt{(g+1)/(2g)}$ with this method. The method to reduce the supply can be extended to include more number of bits and it is equivalent to using pulsewidth modulation for most significant bits and amplitude modulation for the least significant bits. The select waveform will be equivalent to discrete version of trapezoidal waveform, which is a good choice for reducing power consumption as well as the supply voltage.

VI. Results

The technique is demonstrated with a 32×32 matrix LCD by displaying 128 gray shades. It can use any one of the three select waveforms shown in Table I to scan the display. We have measured the current in the analog part of the drivers and have measured the current for the 3-select waveforms and 4 images as shown in the table. It was measured with Agilent 34410A digital multi-meter by integrating for 2 s. Power consumption is proportional to square of the current. Hence, the ratio of square of the current of select waveforms in rows 1 and 2 (profiles 'a' and 'c') to that of the waveform 3 (profile-b) are expressed in % in the Table I for the sake comparison. Theoretical values obtained through analysis are shown within parenthesis in the first column. Image in first column consists of all the 128 gray shades occurring equal number of times as per the original assumption. Although the analysis does not take in to consideration the voltage (gray shade) dependence of capacitance; it can

TABLE I
CURRENT IN THE ANALOG PART OF THE DRIVER CIRCUIT (VOLTAGE LEVEL GENERATOR) FOR THE 3-SELECT WAVEFORMS AND A FEW IMAGES

Images-> Select Waveform				
	3.797mA 89% (86%)	3.078mA 101%	3.462mA 88%	3.599mA 83%
	3.773mA 88% (80%)	3.166mA 107%	3.428mA 87%	3.606mA 84%
	4.020mA 100%	3.056mA 100%	3.672mA 100%	3.944mA 100%

Note: Ratio of power dissipation is expressed in % and the values within the parenthesis were obtained through analysis.

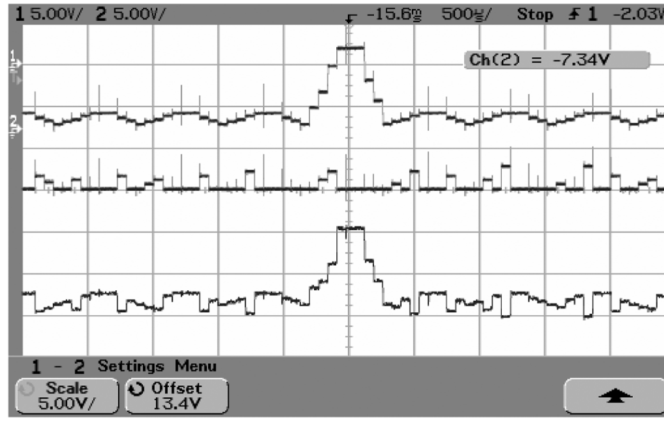


Fig. 10. Waveforms captured using an oscilloscope viz. from the top: row waveform, column waveform and waveform across the pixel; in the same order.

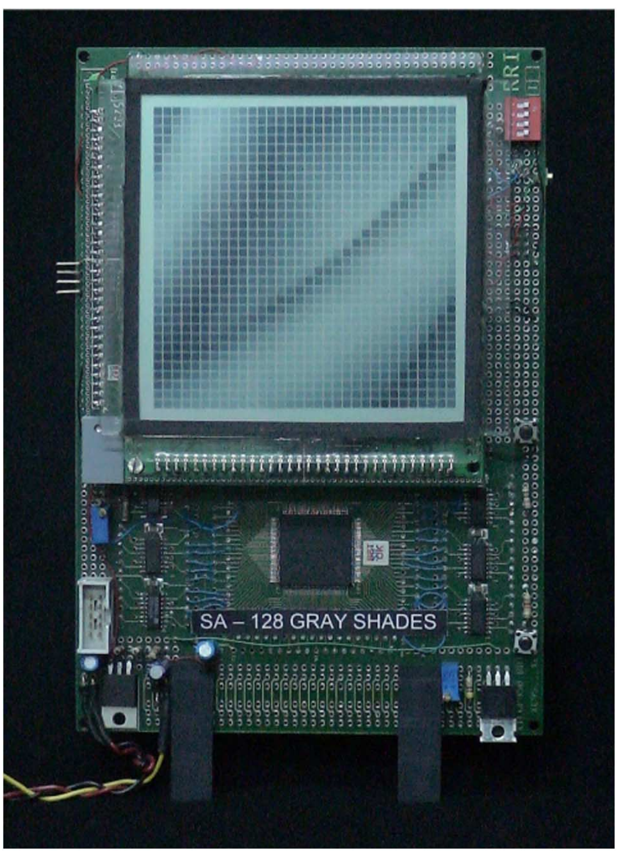


Fig. 9. Photograph of the prototype that is capable of displaying 128 gray shades.

be seen that the profile-b consumes the maximum power under multiplexed condition as predicted in the analysis. Similarly, the column 2 of the table confirms that the power consumption is the least for the profile-b (as predicted in the analysis) when bilevel images are displayed when the image is a checkerboard pattern (bilevel image with just ON and OFF pixels). Power dissipation depends on the image statistics as evident from the entries in columns 3 and 4 of the table. It is important to note that the results in the table do not reflect the reduction in power dissipation due to 24% reduction in supply voltage when the select pulse of MSB is reduced by $(1/\sqrt{2})$. Overall the power dissipation is 73% of the power dissipation of successive approximation technique with ramp (profile-a). Photograph of the prototype is shown in Fig. 9. Typical select waveform, data waveform and the waveform across the pixel are shown in Fig. 10.

VII. CONCLUSION

We have achieved low power consumption and low voltage operation when gray shades are displayed with a new select waveform. This method can also be used reduce the power consumption and supply voltage of multi-line addressing techniques. Hardware complexity of the drivers of successive approximation techniques is the least of all the techniques for gray shades and a good reduction in power consumption and supply voltage of the driver circuit can be achieved without increasing the hardware complexity of the drivers with just a few analog multiplexers [2], [4]. These multiplexers are common to all stages of the drivers and therefore independent of number of rows and columns in the display.

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