A Successive Approximation Technique for Displaying Gray Shades in Liquid Crystal Displays (LCDs)

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***Abstract*—A successive approximation technique that is based on the conventional line-by-line-addressing is proposed. A large number of gray shades can be displayed without flicker by using low-cost liquid crystal display drivers that are designed to drive the pixels to either ON or OFF states in bilevel displays.**

***Index Terms*—Gray shades, liquid crystal displays (LCDs), matrix addressing, multiplexing.**

I. Introduction

SUCCESSIVE approximation is a well-known analog to digital conversion technique. A voltage can be converted to its equivalent digital number in a fixed number of clock cycles and the conversion time is independent of the amplitude of the signal. A similar process is proposed to control the light transmission through the pixels in LCDs to display gray shades. Techniques for displaying gray shades in passive matrix LCDs are reviewed briefly in the next section.

II. Background

Twisted Nematic (TN) and Super TN effects are the most popular electrooptic effects in LCDs. They exhibit the RMS response to the applied electric field. Slow response of the LCDs is exploited to display gray shades by applying data voltages corresponding to either ON or OFF state during each time interval depending on the gray-shade data. The number of gray shades that can be displayed in a cycle consisting of "g" time intervals is $(g+1)$. The time interval could be the select time in each of the "g" frames as in frame modulation [1] or it could be a short duration within the select time as in pulse-width modulation [2]. Frame modulation exhibits flicker, and pulse-width modulation will have poor brightness uniformity of pixels when the number of gray shades is large. Amplitude modulation may be used to display a large number of gray shades in matrix LCDs with just four time intervals [3], [4]. Although there is no limit on the number of gray shades, analog-type column drivers or digital drivers that are capable of applying a large number of voltages are necessary. Power consumption of the analog drivers and the hardware complexity of the digital drivers are high for practical application. The amplitude of the select pulses is modulated in the ratio 4:2:1 during three frames in the row voltage pulse amplitude modulation technique [5] to display eight gray shades. Selection ratio (the ratio of the RMS voltage across ON pixels to that of the OFF pixels) of this technique is not the maximum, and, hence, the contrast will be poor. Several addressing techniques for displaying gray shades are reviewed in reference [6]. A successive approximation technique to display 16 gray shades was presented in ASID conference [7]. This technique is based on multiline addressing (MLA), and it achieves the maximum selection ratio as compared to the multiline addressing technique in [5]. Line-by-line addressing technique [8], [9] is popular in many applications. A successive approximation technique that is based on the line-by-line addressing is presented in this paper.

III. Principle

The electrooptic response of LCDs (in the RMS regime) depends on the energy delivered to pixels. Therefore, the desired RMS voltage can be achieved by delivering energy corresponding to each bit in different time intervals so that the energy delivered to the pixels in "g" time intervals is proportional to the gray-shade data. Approach to realization of successive approximation technique in combination with the line-by-line addressing technique is outlined next.

A matrix display can be scanned by using one bit, say "bit-j" of the "g-bit" gray-shade data at a given instant of time. Let V_x and V_y be the voltages applied to the select and data electrodes, respectively. Voltage across the pixel that is located at the intersection of the electrodes is $(V_x - V_y)$, and the energy delivered to the pixel will be $(V_x - V_y)^2 T$, whereas T is the duration of the select pulse. The selection ratio of the addressing technique is a maximum [8] when the ratio

$$\frac{V_r}{V_c} = \sqrt{N}. \tag{1}$$

Here, V_r and V_c are the amplitude of the select and data voltages of the conventional line-by-line addressing technique. It is useful to note that the condition in (1) has an infinite number of solutions because the ratio, and not the absolute values of two voltages, has to be equal to $\sqrt{N}$. Hence, kV_r and kV_c will also satisfy the condition for the maximum selection ratio. Our objective is to deliver energy that is proportional to the weight of a bit of the gray-shade data to the pixels during a time interval.

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Instantaneous voltages are chosen such that the condition for maximum selection ratio is satisfied

$$V_x = \pm\sqrt{2^j}.V_r \quad \text{and} \quad V_y = \pm\sqrt{2^j}.V_c. \tag{2}$$

Select voltage is common to all the pixels in the address line. Hence, the sign of the data voltage is chosen to be the same as the select voltage when the bit-j is "logic-0" and it is chosen to be opposite otherwise (when the data bit is "logic-1"). Then, the energy delivered to the pixel during a time interval T will be proportional to the bit weight (2^j) as shown in (3)

$$E_{\text{select\_time}} = T(V_x - V_y)^2 = T2^j\left(V_r^2 \mp 2V_rV_c + V_c^2\right). \tag{3}$$

The last term in (3) is the same as that of the conventional line-by-line addressing technique. Actual energy delivered to the pixels will depend on the sign of the mid term: $2^{(j+1)}V_rV_cT$. Energy delivered to the pixel is higher when the bit is "logic 1" as compared to that when the data bit is "logic 0." The first and the last terms, i.e., $2^jV_r^2T$ and $2^jV_c^2T$ are the inevitable constant (independent of the data) terms that are present in the addressing techniques of the RMS responding matrix LCDs. The RMS voltage across the pixels will correspond to gray-shade data if the pixels are selected with "g" select voltages (corresponding to the "g" bits) successively by applying the select voltage to one electrode of the pixels and simultaneously applying the data voltages (corresponding to the respective bits) to the other electrode of the pixels. Part of the binary decision tree, i.e., the first three of the "g" stages in the successive approximation technique are shown in Fig. 1. A technique that is based on the line-by-line addressing is described next.

IV. Successive Approximation Technique Based on Line-by-Line Addressing

A. Technique

Consider a matrix display with pixels located at the intersection of two sets of electrodes (scanning and data) that are orthogonal to each other. Let N and M be the number of scanning electrodes and the data electrodes, respectively. Value of the "g-bit" gray-shade data $(d_{g-1}, d_{g-2}, \cdots, d_1, d_0)$ is

$$\sum_{j=0}^{(g-1)} k_j 2^j \quad \text{where in} \quad k_j = \begin{cases} +1 & \forall \quad d_j = \text{`logic–0'} \\ -1 & \forall \quad d_j = \text{`logic–1'} \end{cases}. \tag{4}$$

The N scanning lines in the matrix display are selected sequentially one at a time as in the conventional line-by-line addressing technique. Let $+\sqrt{2^{(g-1)}}V_r$ be the select voltage during a time interval. Then the most significant bit (MSB) of the gray shade is used as the data of the pixel during this time interval and the corresponding data voltages are applied to all the M data lines during this time interval.

Data voltage is either $+\sqrt{2^{(g-1)}}V_c$ (when the MSB is "logic-0" and the sign of the select voltage is positive) or $-\sqrt{2^{(g-1)}}V_c$ (in case the MSB is "logic-1" and the select voltage is positive). This time, the interval is followed by another with $+\sqrt{2^{(g-2)}}V_r$ as the select and $\pm\sqrt{2^{(g-2)}}V_c$ as the data voltages corresponding to the next significant bit (d_{g-2}). Similarly, the address line is selected $(g-2)$ times with voltages corresponding to rest of the $(g-2)$ bits with both select and data voltages modulated by a factor $\sqrt{2^j}$ and the corresponding bit (bit-j) is used as the data bit. Addressing is complete when all (N) the address lines have been selected with the "g" select voltages. Nonslected address lines are at ground potential, a mid-voltage with low output impedance. While "g" frames are adequate to complete the addressing, some DC voltage will be present across the pixels at the end of the "g" frames. The presence of DC voltage across pixels results in deposition of oppositely charged ionic particles on the electrodes. It could lead to slow electrochemical reactions and reduce the life of the

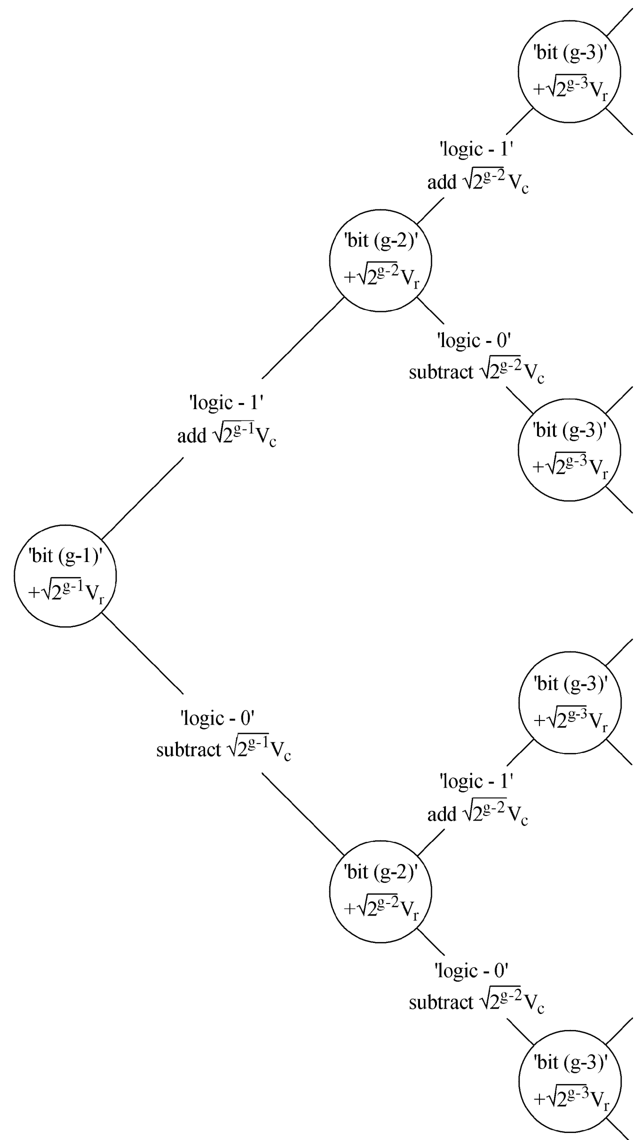

Fig. 1. Part of the binary decision tree (first three of the "g"stages) that will lead to the desired RMS voltage across the pixel in "g" time intervals. The select voltages are inscribed inside the nodes and the data voltages are shown on the branches.

display. Hence, the polarity of the scanning and the data waveforms are reversed periodically to achieve a DC free operation. A cycle is complete when the display is scanned (by selecting the N address lines) with $(2g)$ select voltages to ensure DC free operation. Hence, $(2g+1)$ voltages in the scanning waveforms, $(2g)$ voltages in the data waveforms and $(2g)$ time intervals are necessary to display 2^g gray shades without any DC voltage across the pixels. Although the number of time intervals is marginally higher than that of amplitude modulation, it is small as compared to the time intervals that are necessary to display 2^g gray shades if frame or pulse-width modulation is used. Number of voltages in the data waveforms is small (less by $2(2^g - g - 1)$) in successive approximation technique as compared to the amplitude modulation. Just four (two select and two data) voltages are necessary to scan the display at a given instant of time. This fact could be used to reduce the hardware complexity of the drivers. Off-the-shelf drivers that are used in alphanumeric displays with pixels driven to one of the bilevels (ON or OFF states) can be used along with analog multiplexers that are common to all the drivers. Hence, the successive approximation technique is favorably placed from point of power consumption and the hardware complexity of the drivers as compared to the amplitude modulation.

B. Analysis

Expressions for the RMS voltage across the pixels are as follows:

$$V_{\text{pixel}}(\text{RMS}) = \sqrt{\frac{T.\sum_{j=0}^{(g-1)} 2^j (V_r - V_c)^2 + (N-1)T.\sum_{j=0}^{(g-1)} 2^j V_c^2}{g.N.T}}. \quad (5)$$

It simplifies to

$$V_{\text{pixel}}(\text{RMS}) = \sqrt{\frac{(2^g-1)\left(V_r^2 \mp 2V_rV_c + NV_c^2\right)}{g.N}} \quad (6)$$

$$V_{\text{ON}}(\text{RMS}) = \sqrt{\frac{(2^g-1)\left(V_r^2 + 2V_rV_c + NV_c^2\right)}{g.N}} \quad (7)$$

$$V_{\text{OFF}}(\text{RMS}) = \sqrt{\frac{(2^g-1)\left(V_r^2 - 2V_rV_c + NV_c^2\right)}{g.N}}. \quad (8)$$

The expressions for the RMS voltage across the ON and OFF pixels in (7) and (8) are same as that of the conventional line-by-line addressing except for the factor $\sqrt{(2^g-1)/g}$. Hence, the selection ratio and the condition for the maximum selection ratio are also same as that of the conventional line-by-line addressing as shown in (9)

$$\frac{V_{\text{ON}}}{V_{\text{OFF}}} = \sqrt{\frac{\sqrt{N}+1}{\sqrt{N}-1}}, \text{ a maximum when } \frac{V_r}{V_c} = \sqrt{N}. \quad (9)$$

Supply voltage of the drive electronics is obtained by estimating the maximum swing $(2.\sqrt{2^{(g-1)}}.V_r)$ in the addressing waveforms. The OFF pixels are biased near the threshold of the LCD to achieve a good contrast in the display. Hence, the supply voltage of the drive electronics can be obtained by equating RMS voltage across OFF pixels to threshold voltage and substituting for V_r and V_c as shown in (9)

TABLE I
SUPPLY VOLTAGE—A COMPARISON

Number of gray shades 2^g	Percentage increase in supply voltage $\sqrt{\frac{g\,2^{(g-1)}}{2^g-1}}.100$ (%)	Maximum number of lines that can be multiplexed if the supply voltage of the drivers is limited to 30 V
4	15.47	282 (1240)
8	30.93	214 (953)
16	46.06	167 (757)
32	60.64	135 (618)
64	74.57	111 (518)
128	87.82	94 (442)
256	100.39	80 (385)

$$V_c = \frac{V_{\text{th}}}{\sqrt{2\left(1-(1/\sqrt{N})\right)}} \quad \text{and}$$

$$V_r = \frac{\sqrt{N}.V_{\text{th}}}{\sqrt{2\left(1-(1/\sqrt{N})\right)}} \quad (10)$$

$$V_{\text{Supply}} = \sqrt{2^{(g-1)}}2.V_r = \sqrt{\frac{g2^{(g-1)}}{2^g-1}}\left(\frac{2\sqrt{N}}{\sqrt{2\left(1-(1/\sqrt{N})\right)}}\right)V_{\text{th}}. \quad (11)$$

Here, V_{th} is the threshold voltage of the liquid crystal mixture in the display. The second term in (11) is the supply voltage of the conventional line-by-line addressing. Hence, the first term in (11) is the factor by which the supply voltage will increase if gray shades are displayed using successive approximation. Percentage increase in the supply voltage as compared to the case when just bilevel images are displayed is given in Table I.

An increase in supply voltage is moderate, and it is the price paid for the reduction in hardware complexity of the drive electronics. For example, the supply voltage doubles when the number of gray shades is increased by a factor 128 (i.e., from 2 to 256). Although, the analysis presented in this section is for the technique based on the line-by-line addressing, the increase supply voltage with the number of gray shades will be same even if the successive approximation is based on any other technique for addressing matrix LCDs, ex.: The successive approximation technique based on multiline addressing [7].

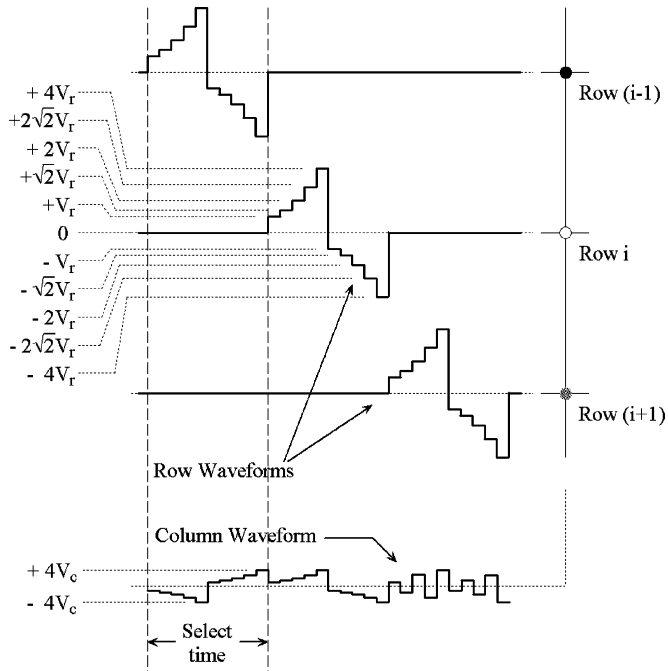

Fig. 2. Typical waveforms of the successive approximation technique to display 32 gray shades using 10-N time intervals to complete a cycle that includes polarity reversal for a DC free operation. All the ten select pulses are clustered together and DC free operation is ensured with in a frame. It is one extreme of the many possible scanning sequences.

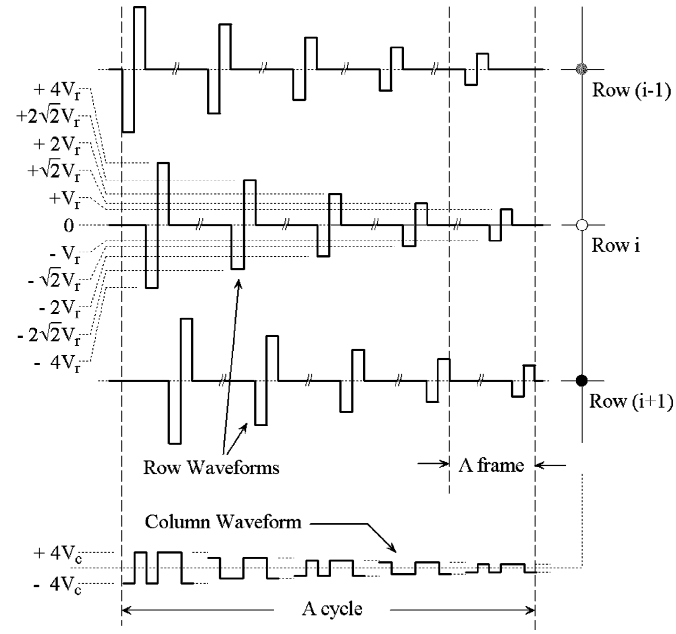

Fig. 4. Typical waveforms of the successive approximation technique to display 32 gray shades using 10-N time intervals. These time intervals are distributed in "g" frames and the DC free operation is ensured with in a frame by introducing the polarity reversal in two successive time intervals.

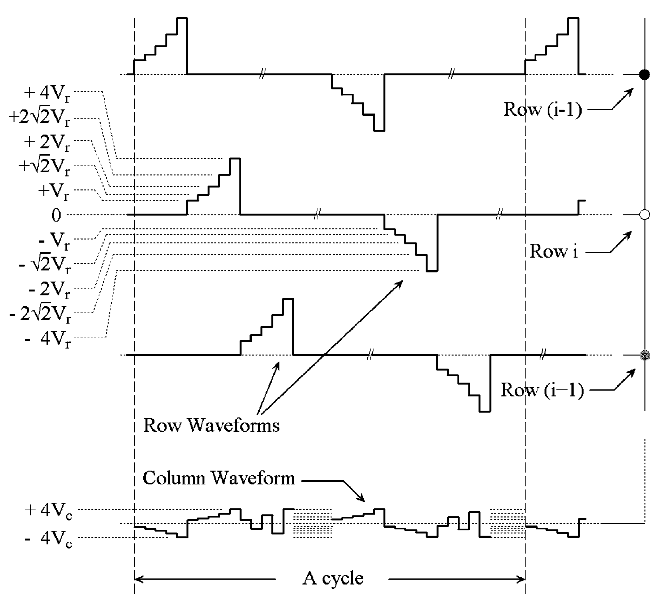

Fig. 3. Typical waveforms of the successive approximation technique to display 32 gray shades, when the polarity reversal is distributed into two frames and the five select pulses are clustered. Number of time intervals and the RMS voltage across the pixels will not change but the frequency spectrum across the pixels will be different.

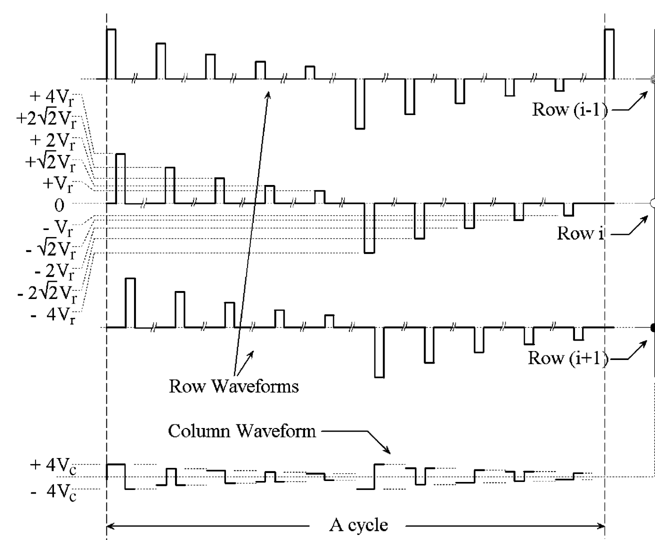

Fig. 5. Typical waveforms of successive approximation techniques for displaying 32 gray shades with ten time intervals. Select pulses and the polarity inversion are distributed into different frames. It is the other extreme of the many possible scanning sequences. It is well suited for suppressing frame response in fast responding displays.

C. Reducing the Supply Voltage

Waveforms shown Figs. 2–5 correspond to the line-by-line addressing proposed by Alt and Pleshko [8] with three and two voltage levels in the scanning and data waveforms, respectively. The following methods can be used to reduce the supply voltage.

1) Scanning and data waveforms can be transformed into waveforms with four voltage levels. This method was proposed by Kawakami *et al.* [9] to reduce the supply voltage of the bilevel displays using the line-by-line addressing. Most of the commercially available LCD drivers are designed for this technique and they have four voltage levels in both scanning and data waveforms. A similar voltage transformation can be applied to the successive approximation technique based on the line-by-line addressing. Apart from reducing the supply voltage, off the self, low-cost drivers can be used to display a large number of gray shades. About 50% reduction in supply voltage

can be achieved. The maximum number of lines that can be multiplexed when the supply voltage of the drivers is limited to 30 V is shown in Table I. Threshold voltage of the LCDs range from 1 to 3 V and the maximum number of lines calculation is based on assuming an average value of 2 V. The values given within the parenthesis are based on assuming threshold to be 1 V and from these values it is clear that a large number of lines can be multiplexed even when 256 gray shades are displayed by using liquid crystals with lower threshold voltage.

2) The supply voltage can also be reduced by adapting successive approximations to the multiline addressing techniques as proposed in [7]. Supply voltage can be reduced by more than 50% if the number of lines that are selected simultaneously is greater than five. In fact, a minimum supply voltage for a specified number of scanning lines (N) can be achieved when the number of scanning lines that are selected simultaneously is an integer close to $\sqrt{N}$. Good reduction in supply voltage can be achieved by selecting four to eight scanning lines simultaneously in most of the displays (N in the range of a few hundreds).

D. Scanning Sequences

Analysis presented in the Section IV-B is independent of the scanning sequences, the order in which the scanning electrodes are selected with different select voltages. Brightness uniformity of pixels depends on the scanning sequence because the number of transitions in the waveform and the frequency spectrum across pixels is determined by the scanning sequence. Pixels in LCDs are equivalent to variable capacitors and just as in complimentary metal oxide semiconductor (CMOS) circuit; the power is consumed only when there is transition in the voltage, i.e., while charging and discharging the pixels. Hence, the power consumed in the LCD drivers is determined by the scanning sequence because the magnitude of the transitions and the number of transitions also depend on the scanning sequence apart from the data of the pixels. A few scanning sequences are outlined here.

1) A scanning electrode (address line) can be selected with all ($2g$) the time intervals successively before selecting another address line. Select voltages are clustered with in a short time interval as shown in Fig. 2. Here, again, the order in which the select voltages are applied can be changed and it has many ($(2g)!$) possible sequences. Monotonically increasing or decreasing select voltages are advantageous because the power consumption will be less as compared to the waveforms with a large swing in the voltages [10]. Typical scanning (row) waveforms with monotonically increasing and decreasing select voltages as well as the corresponding data (column) waveforms are shown in the Fig. 2. It includes polarity reversal for a DC free operation. For example, ten select voltages are used in the scanning waveforms to display 32 gray shades and ensure DC free operation.
2) Polarity reversal of the drive waveforms can be distributed into two frames as shown in Fig. 3. The flicker frequency, the frequency at which the flicker starts appearing, will be less (about half) than that of the case 1.
3) The time intervals can also be distributed into several frames and one such possibility is shown in Fig. 4. Here, the select voltages are distributed in to "g" frames and the polarity of the voltages is reversed with in a frame. Flicker frequency will be much lower as compared to cases 1 and 2. Power consumption of the drivers will be higher because the number of transitions is high and the magnitude of the transitions during the polarity reversal is large.
4) Polarity reversals may be distributed into different frames as shown in Fig. 5. It is an extreme case of distributing the select time intervals into several frames. Power consumption will be lower than that of case 3, but higher than cases 1 and 2. The flicker frequency will be the least in this case. This approach is useful for suppressing the frame response as discussed in [11].

There are many permutation and combinations of scanning sequences that are intermediate to the clustered and distributed sequences presented in this section. Polarity reversal adds another dimension to it. A careful choice of the scanning sequence will result in enhanced performance of the display.

E. Voltage Transformation for Reducing the Supply Voltage

A successive approximation technique that is based on the conventional line-by-line addressing has $(2g+1)$ and $(2g)$ voltages in the scanning and data waveforms, respectively. However, at a given instant of time, just two voltages are applied to the scanning and data electrodes. Scanning electrodes have either V_{select} or $V_{\text{nonselect}}$ voltages, while the data electrodes have $V_{\text{logic}-0}$ and $V_{\text{logic}-1}$. A set of multiplexers that are external to the integrated circuits of the drivers can be used to select the voltages corresponding to each bit of the "g-bit" gray-shade data. Amplitude of the scanning waveforms doubles when the polarity inversion is included in the addressing waveforms for a DC free operation. A method to reduce the supply voltage that is based on the technique proposed by Kawakami *et al.* [9] is described next.

1) A voltage $\sqrt{2^i}.V_c$ is added to the scanning and the data voltages when the polarity of the select voltage is positive. Scanning voltages V_{select} and $V_{\text{nonselect}}$ are transformed to $\sqrt{2^i}(V_r+V_c)$ and $\sqrt{2^i}.V_c$, respectively. Similarly, the data voltages $V_{\text{logic}-0}$ and $V_{\text{logic}-1}$ are transformed to $\sqrt{2^i}.(2.V_c)$ and 0, respectively.
2) Add $\sqrt{2^i}.V_r$ to the scanning and data voltages otherwise (negative polarity), so that the instantaneous voltages V_{select}, $V_{\text{nonselect}}$, $V_{\text{logic}-0}$, and $V_{\text{logic}-1}$ are transformed to 0, $\sqrt{2^i}.V_r$, $\sqrt{2^i}(V_r-V_c)$ and $\sqrt{2^i}(V_r+V_c)$, respectively.

Voltage swings in the scanning waveforms decreases by $\sqrt{2^j}(\sqrt{N}-1)V_c$ and the voltage swing in the data waveforms increases the same amount, i.e., $\sqrt{2^j}(\sqrt{N}-1)V_c$). Supply voltage of the scanning and data drivers are equal to

$$V_{\text{supply}} = \sqrt{2^{(g-1)}}(V_r+V_c) = \sqrt{\frac{g2^{(g-1)}}{2^g-1}}\left(\frac{(\sqrt{N}+1)}{\sqrt{2\left(1-(1/\sqrt{N})\right)}}\right)V_{\text{th}}. \quad (12)$$

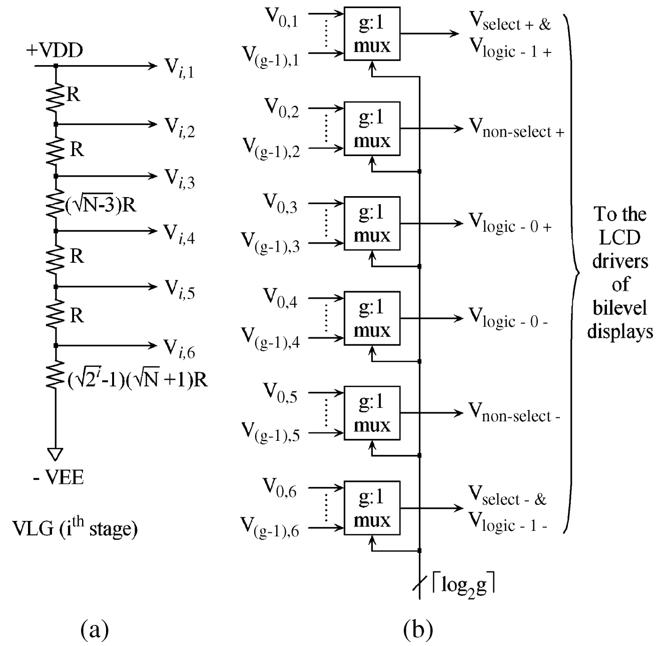

Fig. 6. Resistor network to generate the voltage levels corresponding to one bit of the gray-shade data. The top five resistors are the same from MSB to LSB. R_i, the lower most of the resistors depends on the bit. Here, $i = 0$ corresponds to the MSB and the resistor value is zero. The resistance increases as one moves to the next significant bits. The LSB has the highest resistance value and "i" will $(g - 1)$.

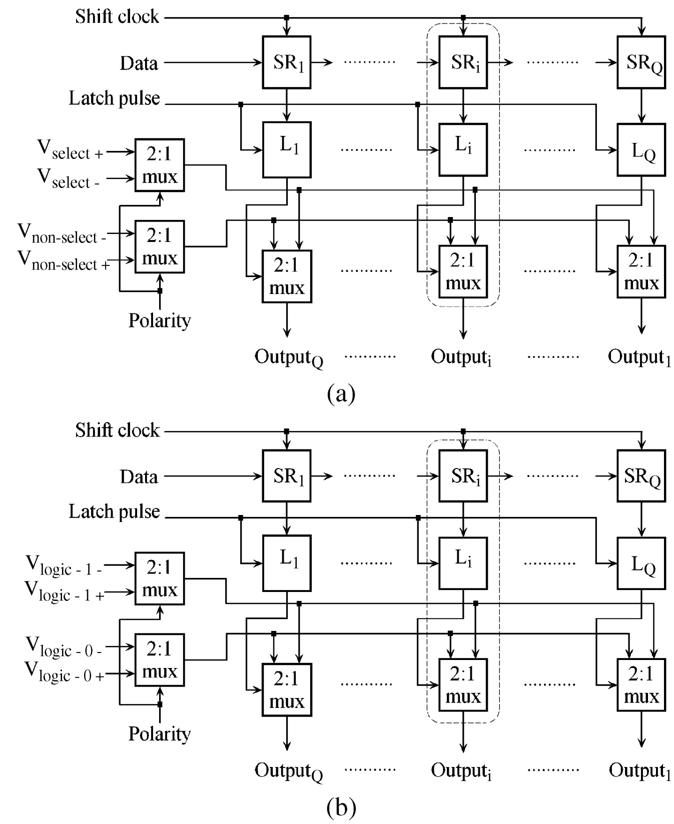

Fig. 7. Schematic diagram of the drivers with Q stages and an equal number of outputs. Both the scanning (row) and data (column) drivers are identical except for the input voltages. Select and data voltages from the multiplexers of (b) are connected to the row and column drivers as shown in (a) and (b), respectively.

Increased swing in the data waveforms and the supply voltage of the data drivers is the price to be paid for decreasing the overall supply voltage of the display. The reduction in supply voltage is $((\sqrt{N}+1)/2\sqrt{N})$, and it approaches 50% when the number of scanned lines is high. It is important to note that the waveform across the pixels will not change due to the transitions because a common voltage is added to both the scanning and data voltages.

F. Voltage Level Generator

A voltage level generator (VLG) is designed to generate the voltages that are in the scanning and data waveforms. A resistor network that corresponds to a bit of the gray-shade data is shown in Fig. 6(a). Unlike the Alt and Pleshko technique [8], the data voltages for the positive and negative polarities are different in the technique proposed in [9]. It is preferable to match the four resistors (R) in each stage of the VLG to ensure good brightness uniformity of the pixels. Resistor $R_i = (\sqrt{2^i} - 1)(\sqrt{N} + 1)R$ $i = 0 \forall \mathrm{MSB}$ and $(g - 1) \forall \mathrm{LSB}$ ensures that the amplitudes of the select and data voltages $V_{i,1}$ to $V_{i,6}$ are in the right ratios. The resistor R_i is zero for the MSB. The VLG for the MSB is same as that of VLG in a bilevel display. Here, a transformation $i = (j - g + 1)$ is used to arrive at the resistor value R_i where in "j" is the index of the data bits in the analysis presented in Section IV-B. Six analog multiplexers ($g : 1$) shown in Fig. 6(b) are used to select the scanning and data voltages from one of "g" VLGs depending on the bit used to scan the display at a given instant of time.

G. Display Drivers

Scan (row) and data (column) drivers are similar except for the clock frequency. Data drivers operate at higher clock frequency as compared to the scan drivers because the data corresponding to all the columns have to be shifted in to the data drivers during each select time. The supply voltage of the controller is usually lower than that of the display drivers. A common rail is necessary between the controller and the display drivers to transfer the data using clock and control signals. Some drivers have the most positive voltages of its logic circuits (shift register and latch) and the analog output section of the drivers tied together to form a common rail. VLG shown in Fig. 6(a) is suitable for the systems with most positive voltage as the common voltage. In case the most negative voltage is used as the common rail, the resistor R_i in the VLG has to be shifted to the top and then the most negative voltage of all the VLGs, drivers as well as the controller can be connected together. The row driver and the column driver that are used to drive the scan and data electrodes, respectively, are shown in Fig. 7. The row driver and the column drivers are similar except for the fact that the data is shifted in to the column drivers is M times faster than that of the row driver.

H. Controller

A $g : 1$ digital multiplexer to select one of the "g" bits at a given instant of time and the select signals for the analog as well as the digital multiplexers are the two additions that are necessary to the controller designed for displaying bilevel information. In summary, the $(g-1)$ VLGs, the six analog multiplexers, a $(g : 1)$ data selector (to select one of the "g" data bits) and a

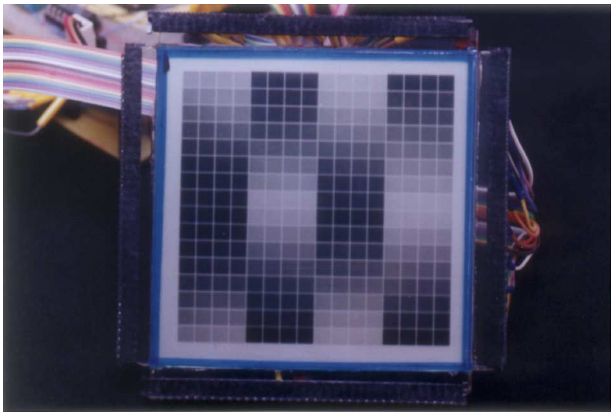

Fig. 8. Photograph of a 16 × 16 matrix twisted nematic LCD displaying eight gray shades using successive approximation based on the line-by-line addressing.

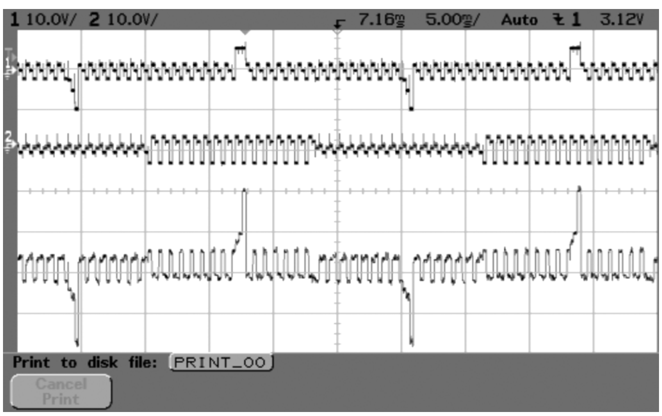

Fig. 9. Typical addressing waveforms (starting from the top: a row waveform, a column waveform, and waveform across a pixel at the intersection of row and column) when the supply voltage is reduced as discussed in Section IV-E. The most positive voltage of the drivers and the controller are tied together to form the common rail.

circuit to generate the select signals for the multiplexers are the additional circuit necessary to upgrade a bilevel LCD to display gray shades using successive approximation.

I. Results

Photograph of a 16 × 16 matrix display displaying eight gray shades (using HLCD 44100 LCD drivers) is shown in Fig. 8. Typical addressing waveforms when the most positive voltage $V_{\mathrm{select}+}$ (also $V_{\mathrm{logic1}-}$) is the common positive rail (V_{DD}) are shown in Fig. 9.

V. Conclusion

The gray-shade techniques are compared in Table II. Successive approximation can be combined with any of the addressing technique for the RMS responding LCDs to display a large number of gray shades. The idea of replacing pulse in an addressing technique with "g" pulses is basic in nature and this ensures that the analysis presented in this paper will hold good even when it is implemented with any other technique. This approach opens up the possibility of using drivers that are in bilevel displays (with pixels in either ON or OFF states) and, yet, achieve a large number of gray shades with out flicker because the number of time intervals is small (just equal to logarithm of the number of gray shades to the base two). An additional circuit to be incorporated in the controller and the VLG to displaying gray shades is not significant.

TABLE II
Techniques for Displaying Gray Shades—A Comparison

Parameter	Frame and pulse-width modulation	Amplitude modulation	Successive approximation
Number of time intervals to display 2^g gray shades	$2\,(2^g-1)$	4	$2\,g$
Number of voltages in the scanning waveforms	3	$2\,(2^g-1)$	$(g+1)$ But just 3 or 4 at a given instant of time
Number of voltages in the data waveforms	2	$2\,(2^g-1)$	$(2\,.g)$ But just 2 or 4 at a given instant of time
Number of gray shades	About 16	Unlimited	Large, (greater than 256)
Supply voltage	Same as the line-by-line addressing	Same as the line-by-line addressing	Higher than the line by line addressing
Flicker	Flicker in frame modulation	No flicker	No flicker
Hardware complexity	Low	High	Low

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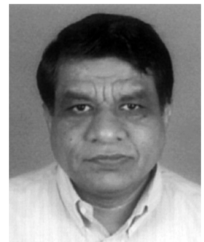

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