Abstract—A small-signal amplifier with three identical MOSFETs in Darlington’s topology is proposed and qualitatively analyzed perhaps for the first time. Unlike CS-MOSFET amplifiers, the voltage gain of the proposed circuit is found considerably higher than unity. This amplifier can be used to amplify audio range signal excursions swinging in 0.1-2mV range. In the narrow-band performance range, the proposed amplifier produces simultaneously high voltage and current gains with low harmonic distortion. These properties offer a flexible application range to the proposed circuit as high-voltage-narrow-band amplifier in permissible audio-frequency range. An additional biasing resistance $R_A$ is to be essentially used in the proposed circuit to maintain its voltage/current amplification property. Variations in voltage gain as a function of frequency and different biasing resistances, temperature dependency of performance parameters like voltage gain, bandwidth, current gain, input/output noises and total harmonic distortion of the amplifier are perused to provide a wide spectrum to the qualitative studies.

Index Terms—Small signal RC coupled amplifiers, darlington amplifiers, common Source MOS amplifiers, triple darlington amplifiers, MOSFET darlington pairs.

I. INTRODUCTION

In general, MOS transistors act as good amplifiers for radio frequency integrated circuits when operated in the saturation region (under specific characteristics) and exhibit capacity to provide high voltage, current and power gains [1], [2]. Concurrently ‘Common Source MOSFET’ has been explored to amplify small-signals with its specific characteristic of high input impedance, low output impedance, high current gain and a voltage gain greater than unity [3]-[6]. Numerous researches explored this MOSFET configuration suitable for developing high speed switching circuits, memory segments, logic gates, buffer amplifiers, power amplifiers and trans-conductance amplifiers [1]-[9].

However, use of CS-MOSFET in Darlington’s topology to develop small-signal audio range amplifiers is still to be established [5], [10]. In this sequence, authors developed two small-signal amplifier circuits using MOSFETs in Darlington pair and explored them as high voltage gain and wideband amplifiers respectively [5].

In the present manuscript, authors proposed a novel circuit of high voltage / high current gain audio-range small-signal amplifier by placing identical CS-MOSFETs in Triple Darlington configuration [11].

Dependency of qualitative performance of the proposed amplifier on various biasing parameters, biasing supply and operational frequency is analyzed and compared with that of high voltage gain Darlington pair MOSFET amplifier [5].

II. CIRCUIT DESCRIPTION

Present work comprises a qualitative comparison between two different circuits of small-signal amplifiers using identical MOSFETs in Darlington’s topology. The first circuit having two identical MOSFETs M1 and M2 in Darlington pair (Fig. 1) is named here as Reference-amplifier whereas the Proposed-amplifier, as depicted in Fig. 2, is obtained by adding an extra MOS transistor M3 in the circuit of reference amplifier. Assembly of three identical MOS transistors in the amplifier circuit of Fig. 2 constitutes a Triple Darlington composite unit [11]. Both the amplifiers include an additional biasing resistance $R_A$ in their circuit design [5], [10]-[13] and use potential divider biasing methodology. Suitably selected passive biasing components provide proper DC biasing to amplifiers of Fig. 1 and Fig. 2, the details of which are summarized in Table I.
PSpice simulation (Student version 9.2) is performed to carry out present investigations [5], [10]-[14]. Observations are procured by feeding the amplifier circuits with 1V AC input signal source, from which, a small-distortion-less AC signal of 1mV for both the amplifiers at 1KHz frequency is drawn as input for amplification purpose. The amplifier of Fig. 1 is found to provide undistorted output for 0.1-10mV AC input signal at 1KHz frequency and is biased with +15V DC biasing voltage. However, +12V DC supply having similar values of biasing parameters, it crops 184.829 maximum voltage gain \( A_{VG} \) (peak output voltage \( V_{OP}=182.039 \) mV), 2.5040K maximum current gain \( A_{ID} \) (peak output current \( I_{OP}=18.204 \) \( \mu \)A), 5.475KHz bandwidth (\( f_{L}=313.132 \)Hz and \( f_{H}=5.789 \)KHz). However, reference amplifier of Fig. 1 produces 130.6 \( A_{VG} \), 7.40K \( A_{ID} \) and 178.01KHz bandwidth (\( f_{L}=293.134 \)Hz and \( f_{H}=178.305 \)KHz). Respective values of voltage and current gains logically set the power gain of the proposed and reference amplifiers considerably larger than unity.

Small-signal AC equivalent circuit of the reference amplifier is drawn in Fig. 4. AC analysis of reference amplifier shows that its equivalent output resistance \( R_{O}=R_{D} || R_{D} \) is lower (\( =909.09Q \)) than the equivalent input resistance \( R_{C}=R_{C} || R_{C} \) (\( =0.5833M\Omega \)), with a phase reversal in output voltage waveform. In addition, AC voltage gain of the reference amplifier is estimated as following -

\[
A_{V(Re,f)} = \frac{-g_{m1}(1 + g_{m2}R_{w} \pm R)}{R_{g} + \left( \frac{1}{r_{d1}} + \frac{1}{r_{d2}} \right) \left( g_{m2}R_{w} - \frac{R_{o}}{r_{d2}} \right) + \left( \frac{1}{r_{d1}} + \frac{1}{r_{d2}} \right)}
\]

On the basis of above equation, the approximate value of AC voltage gain of reference amplifier is figured out to be \( \approx -131.093 \) with computed \( r_{d1}=2.415K\Omega \), \( r_{d2}=93.22K\Omega \), \( g_{m1}=0.144 \)mho and \( g_{m2}=0.0257 \)mho. Negative sign in the expression shows phase reversal of the output voltage which is because the composite unit of MOSFET Darlington pair holds an equivalent CS configuration [1].

In addition, attempts are made to extend the equivalent circuit of Fig. 4 for the proposed amplifier. The upshot is depicted in Fig. 5. Figure suggests that centrally located MOSFET M2 of the proposed amplifier does not allow any significant current to flow from drain to source of M2 with \( g_{m2}=0 \)mho, \( I_{D2}=9.27 \times 10^{-14} \)amp and \( V_{DS}=4.12 \times 10^{-6} \)volts, thereby, producing a capacitive effect in the circuit. Presence of Gate-Bulk-Capacitance of 0.207nF and Bulk-Drain-Zero-Bias-pn-Capacitance of 3.23nF due to the

Fig. 3. Variation of voltage gain with frequency.

![Fig. 3. Variation of voltage gain with frequency.](image)

III. RESULTS AND DISCUSSIONS

The amplifiers of Fig. 1 and Fig. 2 are found to provide fair and distortion-less results for 0.1-10mV and 0.1-2mV AC input signals respectively in 100 Hz to 100 KHz input frequency range at +15V DC biasing voltage. However, when DC biasing to the proposed amplifier is changed to +12V, the circuit provides distortion-less results for 0.1-15mV AC input signal in the similar range of frequency.

![Fig. 4. AC equivalent circuit of reference amplifier.](image)

![Fig. 5. AC equivalent circuit of proposed amplifier.](image)

In addition, attempts are made to extend the equivalent circuit of Fig. 4 for the proposed amplifier. The upshot is depicted in Fig. 5. Figure suggests that centrally located MOSFET M2 of the proposed amplifier does not allow any significant current to flow from drain to source of M2 with \( g_{m2}=0 \)mho, \( I_{D2}=9.27 \times 10^{-14} \)amp and \( V_{DS}=4.12 \times 10^{-6} \)volts, thereby, producing a capacitive effect in the circuit. Presence of Gate-Bulk-Capacitance of 0.207nF and Bulk-Drain-Zero-Bias-pn-Capacitance of 3.23nF due to the

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A dedicated location of M2 in proposed circuit generates an intense capacitance.

Therefore, the combination of Miller’s capacitance and capacitance due to centrally located MOSFET M2 of the proposed amplifier causes an effective reduction in the bandwidth. Hence, during the analysis of equivalent circuit (Fig.5) for AC voltage gain, M2 of the proposed amplifier would be treated as absent. This estimation suggests following expression for the approximate value of AC voltage gain of proposed amplifier-

\[
A_{v(proposed)} \approx \frac{-g_{m1}(1 + g_{m3}R_n - \frac{R}{r_{d3}})}{R_0 + (1 + \frac{1}{r_{d1}})\left(g_{m3}R_n - \frac{R}{r_{d3}}\right) + \left(\frac{1}{r_{d1}} + \frac{1}{r_{d3}}\right)}
\]

Above equation gives AC voltage gain of the proposed amplifier to -238.48 with computed \(r_{d1}=272.11\Omega, g_{m1}=0.262mho\) and \(g_{m3}=0.005mho\).

Total Harmonic Distortion (THD) percentage is also calculated for the reference and proposed amplifiers for 10 significant harmonic terms using following established rule [3], [5].

\[
\%n^\text{th}\ harmonic\ distortion = \%D_n = \left|\frac{A_n}{A_1}\right| \times 100\%
\]

The reference amplifier appears with 1.88% THD whereas it is observed to be 2.84% at +15V DC biasing for proposed amplifier. THD for proposed amplifier further reduces to 2.28% if respective circuit is biased with +12V DC supply. For the mentioned situations, THDs are ranging within the permissible limit for small-signal amplifiers [3].

### TABLE II: VARIATION OF AVG, AIG AND BW WITH TEMPERATURE

<table>
<thead>
<tr>
<th>Temp. (°C)</th>
<th>Fig.1 Amplifier</th>
<th>Fig.2 Amplifier</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AVG</td>
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</tr>
<tr>
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<td>151.85</td>
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<td>7.40K</td>
</tr>
<tr>
<td>50</td>
<td>123.93</td>
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</tr>
<tr>
<td>120</td>
<td>107.97</td>
<td>6.10K</td>
</tr>
</tbody>
</table>

Variation of voltage gain, current gain and bandwidth with temperature is also measured and listed in Table II. It is noticed that both variety of gains gradually decreases at increasing temperature for respective amplifiers. This can be associated with the positive temperature coefficient property of Drain-Source resistance [15]. Perhaps Drain-Source resistance of the composite unit rises with temperature which in turn reduces the effective voltage/current gains [15]. On the other hand, bandwidth of reference amplifier reduces but that of proposed amplifier increases with rising temperature. At increasing temperature, perhaps the series combination of composite unit (having an extra MOSFET capacitance and output coupling capacitor C2 (with 1uF value) in the proposed amplifier circuit causes reduction in effective circuit capacitance which in turn improves the bandwidth [1], [2], [15].

Respective values of input and output noises for the proposed amplifier at 100Hz, 1KHz and 1MHz frequencies are observed and listed in Table III. Usually, resistors and semiconductor devices in electronic circuits are responsible to generate noises during amplification process. Table clearly indicates that levels of input and output noises are significantly low for proposed amplifier and within the permissible limit. Both varieties of noises reduce with elevation of operating frequency. Moreover, it also increases with temperature which is an obvious feature due to generation of more carriers and their higher collision rate at elevated temperature.

![Fig. 6. Variation of maximum voltage gain A_{VG} with V_{CC}.](image)

Effect of DC supply voltage \(V_{CC}\) on maximum voltage gain \(A_{VG}\) for both the amplifiers is depicted in Fig.6. Figure clearly indicates that MOSFET Darlington pair of reference amplifier and Triple Darlington MOSFET unit of proposed amplifier switch-ON at 7V. Reference amplifier produces a fruitful response in 7-40V range of \(V_{CC}\) whereas this range for proposed amplifier limits to only 7-20V. \(A_{VG}\) of the reference amplifier rises nonlinearly at increasing values of \(V_{CC}\) [5]. However it climbs up to a maximum at 15V of \(V_{CC}\) for proposed amplifier, thereafter, decreases rapidly and reaches to a non-significant value at 20V of \(V_{CC}\).

In fact, each MOSFET of the Triple Darlington unit of proposed amplifier holds a threshold voltage \(V_{TQ}=2.831V\). Below 7V of \(V_{CC}\), driving potential to gates of M1 and M2...
MOSFETs are found less than $V_{TO}$. This keeps the triple Darlington unit into OFF state. At 7V of $V_{CC}$, driving gate voltages of M1 and M3 cross the forbidden boundary of $V_{TO}$. This ensures the participation of each MOSFET in the amplification process and therefore voltage gain reaches to a max. As $V_{CC}$ increases beyond 15V, the channel width broadens and causes sudden enhancement in $I_D$ which in turn forces for an abrupt voltage drop across the load and distorts the frequency response curve.

As depicted in Fig. 8, maximum voltage gain decreases almost exponentially at increasing values of additional biasing resistance $R_A$ for both the amplifiers. Voltage gain corresponding to the added resistance $R_A$ acquires its maxim at $R_A \approx 1K\Omega$ for each amplifier. If $R_A$ is removed from the proposed circuit, $A_{VG}$ of the amplifier reaches to a non-significant value 0.013 whereas $A_{VG}$ reaches below unity to a value 0.729. Conclusively, the presence of additional biasing resistance $R_A$ in the proposed configuration is essential to establish ‘Triple Darlington MOSFET unit’ suitable for amplification of small-signals.

Maximum voltage gain highly depends on drain resistance $R_D$ [1], [2], [5], [10]. Its variation with $R_D$ is depicted in Fig. 9. For reference amplifier, voltage gain attains a maxim at $R_D=3K\Omega$, thereafter, decreases rapidly and produces distorted output beyond $4K\Omega$ value of $R_D$. However, for proposed amplifier with $+15V$ or $+12V$ DC biasing, the voltage gain attains a maxim at $R_D=1K\Omega$, then falls down rapidly and produces distorted output beyond $2K\Omega$.

Fig. 7. Variation of maximum voltage gain $A_{VG}$ with source resistance $R_{SR}$.

Variation of maximum voltage gain as a function of source resistance $R_{SR}$ is traced in Fig. 7. For reference amplifier, $A_{VG}$ remains almost unaffected for any change in source resistance [5], [10]. However for proposed amplifier, $A_{VG}$ suddenly increases from 1.44 (at 1 K\Ω) to 187.38 (at 2 K\Ω), thereafter, tends to acquire a saturation tendency at higher values of $R_{SR}$. It is also to mention that respective amplifiers show constancy in maximum voltage gain for $R_{SR}>10K\Omega$.

Fig. 8. Variation of maximum voltage gain $A_{VG}$ with added resistance $R_A$.

Small-signal Common Source MOSFET amplifiers hold high current gain as its prominent feature with a voltage gain just greater than unity. However, the proposed small-signal amplifier, which uses three CS-MOSFETs in a typical Triple Darlington configuration, is explored as high voltage gain amplifier, retaining the high current gain property.

In narrowband performance range (approximately 5KHz) this amplifier can effectively process small-signals ranging below 2mV and its THD at either of the DC supply voltage doesn’t exceed 2.84%, which is well within the tolerance limit of small-signal amplifiers. The proposed amplifier produces constant voltage gain at $R_D>100K\Omega$ and $R_{SR}>10K\Omega$ while shows its optimal performance at $R_S=1K\Ω$ and $R_D=1K\Omega$ in 7-15V range of DC supply voltage.

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### REFERENCES


