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BAB IV TOPIK 3

Sistem *Rectifier Direct Current* (DC) Secara Otomatis Untuk Proteksi Katodik Pada *Stainless Steel* (SS) 303 Menggunakan Larutan NaCl 2,7 ‰; 3,1 ‰ Dan 3,5 ‰

4.1 Abstrak

Perlindungan katodik arus paksa (ICCP) dianggap sebagai metode yang efektif untuk mengurangi korosi struktur tetapi jarang digunakan dalam perlindungan korosi kabel baja kekuatan tinggi untuk kabel jembatan karena lingkungan atmosfer di mana kabel baja terletak hampir tidak dapat memberikan solusi elektrolit untuk sistem ICCP. Namun, air hujan terakumulasi di permukaan kabel dan membentuk aliran air. Kondisi semacam itu dapat digunakan sebagai larutan elektrolit untuk sistem ICCP dari kabel baja kekuatan tinggi. Atas dasar ini, penelitian ini mengusulkan metode ICCP untuk kawat baja kekuatan tinggi di curah hujan lingkungan dan menyelidiki efek dari kepadatan arus perlindungan yang berbeda pada korosi kabel baja dalam simulasi lingkungan air hujan dinamis. Dalam pekerjaan ini, tes waktu dan temperatur lingkungan ditetapkan pada 21 hari dan 38°C, dan 2,7%, 3,1% dan 3,5% Larutan NaCl digunakan sebagai simulasi air hujan. Morfologi korosi kawat baja digunakan untuk mengkarakterisasi derajat korosi secara kualitatif. Penurunan berat (*weight loss*) dan elektrokimia pengukuran digunakan untuk mengkarakterisasi laju korosi secara kuantitatif. Memindai elektron mikroskop dan difraksi sinar-X digunakan untuk menganalisis morfologi mikroskopis dari korosi kawat baja dan komposisi kimia produk korosi, masing-masing. Hasil menunjukkan bahwa dibandingkan dengan kabel baja yang tidak terlindungi, permukaan kabel baja dengan ICCP lebih rata, jumlah dan ukuran lubang korosi berkurang secara signifikan, dan laju korosi menjadi berkurang secara signifikan. Dengan demikian, ICCP memainkan efek perlindungan selama periode pengujian namun efisiensi perlindungan sedikit berbeda di bawah laju aliran yang berbeda

Kata Kunci : Korosi, *Impressed Current Cathodic Protection* (ICCP)

4.1 Pendahuluan

Korosi merupakan salah satu masalah yang menimbulkan kerugian dalam industri. Kerusakan akibat korosi, seperti: kegagalan material, kegagalan perangkat, dan kegagalan sistem operasi, memiliki dampak ekonomi yang signifikan. *National Association of Corrosion Engineers* (NACE) melakukan studi tentang kerugian langsung yang diakibatkan korosi memiliki nilai yang sangat tinggi, diperkirakan sekitar 276 milyar dolar AS atau senilai dengan 3,1 % dari gross domestic product (GDP)(Ahmad, 2006). Perhitungan ini termasuk biaya pemeliharaan, penggantian material, jam kerja, kehilangan keuntungan karena penghentian produksi, kekecewaan pelanggan, biaya administrasi, kerugian fisik, dan pembuangan. Oleh karena itu, korosi harus dikendalikan. Sangat penting bagi perekonomian dan keamanan (P. R. Roberge, 2019)

Korosi tidak dapat dihilangkan tetapi dapat dicegah dengan melindungi material dari lingkungan. Salah satunya adalah proteksi katodik pada sistem anoda korban. Proteksi katodik dari sistem anoda korban telah banyak digunakan. Desain yang digunakan adalah kombinasi pengalaman dan data eksperimen (J. Xiao ,et al., 2011) Namun, kegagalan proteksi katodik tidak hanya berdampak pada kerugian ekonomi, tetapi juga pada keselamatan jiwa manusia dan lingkungan.

Logam merupakan salah satu jenis material yang banyak digunakan dalam industri. Logam dapat rusak oleh korosi. Korosi adalah reaksi elektrokimia antara logam dan lingkungannya yang menyebabkan karat dan degradasi logam (M. G. Fontana, et al., 2018) Bahan logam yang paling banyak digunakan dalam industri adalah baja, dan setiap baja memiliki sifat tergantung pada elemen paduan yang dikandungnya. Nikel (Ni), kromium (Cr), dan mangan (Mn) adalah elemen paduan yang meningkatkan ketahanan korosi dari baja. Berdasarkan struktur kristal, baja tahan karat diklasifikasikan menjadi lima kelompok: austenitic, baja tahan karat, baja tahan karat feritik, baja tahan karat martensit, baja tahan karat dupleks, presipitasi pengerasan baja tahan karat, dilas dan non-ferromagnetik. Baja tahan karat austenitik yang mengandung unsur Cr dan Ni diberi nomor urutan 300 dan 200 untuk Cr, Ni dan Mn (A. S. G. D. Sheets ,2013).Salah satu jenis baja

tahan karat austenitik yang banyak digunakan di sektor industri dan non industri adalah seri SS304. Baja jenis ini dapat digunakan di berbagai industri seperti kimia, makanan dan farmasi (B. C. Troconis ,et al., 2020)

Meskipun baja tahan karat, namun masih dapat diserang oleh korosi seperti seragam korosi, korosi pitting atau korosi retak tegangan. Oleh karena itu, diperlukan penelitian tentang korosi ketahanan baja tahan karat itu sendiri. (Loto ,et al., 2013) melakukan uji ketahanan korosi pada stainless baja 304 dengan mereaksikannya dalam larutan asam. Reaksi antara baja SS 304 dan asam sulfat menyebabkan korosi pitting yang signifikan pada permukaan logam. Di sisi lain, penambahan NaCl dapat mengurangi korosi pitting, tetapi laju korosi meningkat [Loto ,et al 2012]. Selain konsentrasi media korosif, laju korosi juga dipengaruhi oleh temperatur dan panjang waktu perendaman (I. Ilyasu, D. S, et,al., 2012).

Beberapa penelitian masih melakukan eksperimen untuk memperpanjang umur logam dari korosi. Untuk fokus logam yang digunakan adalah *stainless steel* karena logam ini sendiri memiliki ketahanan korosi yang baik. Namun, beberapa kondisi menyebabkan stainless steel terkorosi. Sehingga penelitian untuk mengidentifikasi metode yang tepat untuk memperlambat laju korosi pada stainless steel masih relevan.

Korosi adalah penurunan kualitas logam akibat reaksi elektrokimia dengan lingkungan. Menurut (Davis, 2000) korosi didefinisikan sebagai suatu proses yang dialami oleh suatu logam yang bereaksi secara elektrokimia dengan lingkungannya. Saat ini logam banyak digunakan oleh berbagai industri. Salah satu logam yang banyak digunakan adalah paduan baja tahan karat austenitik. Austenitik stainless steel umumnya terdiri dari 2 jenis yaitu type 200 dan type 300. Stainless steel Stainless baja 201 dan stainless steel 304 adalah jenis yang banyak digunakan karena memiliki kualitas yang baik sifat ketahanan korosi.

Baja tahan karat 201 dan 304 dapat dianggap sebagai pengganti satu sama lain di beberapa aplikasi. Oleh karena itu, perlu dilakukan pengujian untuk mengetahui logam mana yang mudah dan sulit terdegradasi karena reaksi elektrokimia antara logam dan lingkungannya. Satu Cara untuk mengurangi potensi degradasi logam akibat proses korosi adalah dengan penambahan inhibitor

dalam sistem. Penambahan inhibitor dalam sistem banyak dipilih karena ini metode ini fleksibel, yang mampu memberikan perlindungan dari lingkungan yang kurang agresif terhadap lingkungan yang sangat korosif. Selain itu, cara ini mudah digunakan dan efektif karena biayanya sedikit tetapi mampu memberikan perlindungan yang luas. (Vasanth, 2003). Banyak zat yang dapat digunakan sebagai inhibitor untuk menurunkan laju korosi, salah satunya adalah zat yang dapat mengikat oksigen di dalam lingkungan sehingga dapat mengurangi proses korosi yang terjadi.

Prinsip proteksi katodik dapat dijelaskan berasal dari situasi seperti ketika dua logam dihubungkan secara elektrik satu sama lain dan ditempatkan/dicelupkan dalam suatu elektrolit, seperti asam atau air laut, elektron akan mengalir dari logam yang lebih aktif ke logam lain karena perbedaan potensial listrik yang merupakan kekuatan pendorong. Anoda, logam yang lebih aktif, memasok arus dan larut secara bertahap menjadi ion dalam elektrolit, dan pada saat yang sama menghasilkan elektron yang diterima katoda (kurang aktif) melalui sambungan logam (galvanik) dengan anoda. Katoda dengan demikian terpolarisasi negatif dan menjadi terlindung dari korosi

Dalam beberapa tahun terakhir, korosi logam dalam lingkungan dinamis telah banyak dieksplorasi. Namun, sebagian besar studi ini telah difokuskan pada perilaku korosi dinamis laut bahan struktural dan pipa. (S.B. Choe and S.-J. Lee, et al 2012) dan (S. Jiang, F, et al 2017) menyelidiki alirannya perilaku korosi yang dipercepat dari baja S355ML yang digunakan dalam struktur kelautan dan baja paduan rendah digunakan dalam pipa dan menemukan bahwa laju korosi baja meningkat dengan laju aliran sedang (G. S. Vasyliiev, 2015) meneliti korosi akibat aliran baja karbon rendah di perkotaan pipa dan menemukan bahwa laju korosi baja menurun dengan peningkatan laju aliran di atas periode waktu. Alasan untuk hasil ini adalah bahwa laju aliran yang lebih tinggi mengurangi ketebalan lapisan difusi dan memungkinkan oksigen mencapai permukaan logam lebih cepat, yang menyebabkan pembentukan dari lapisan pelindung karbonat. Lapisan karbonat bertindak seperti penghalang bagi oksigen dan karenanya laju korosi menurun.

(J. Liang et al ,2013) menilai pengaruh laju aliran air laut pada korosi besi cor dan menjelaskan bahwa laju korosi dipercepat dengan peningkatan laju alir sebagai hasil dari penurunan jalur difusi oksigen melalui lapisan aliran laminar yang berdekatan dengan permukaan kupon. (L. Wei, X. Pang, and K. Gao ,2018) menemukan bahwa laju aliran mengubah tipe dominan X70 baja dari korosi umum (kondisi statis) ke korosi lokal (kondisi dinamis). (B. Evgeny et al 2016) mengeksplorasi perilaku korosi baja karbon rendah di bawah aliran laminar dan turbulen kondisi. Hasil mereka menunjukkan bahwa efek kekasaran permukaan diintensifkan di bawah sepenuhnya aliran turbulen yang berkembang.

(Z.B. Zheng et, al 2014) menentukan kecepatan aliran kritis pasivasi bahan di bawah pelampiasan media korosif melalui eksperimen.

Untuk mengurangi degradasi struktural yang disebabkan oleh korosi, tindakan perlindungan tertentu adalah: biasanya diambil pada struktur, dan perlindungan katodik (CP) adalah anti korosi yang metode (Y. S. Kim, S et,al 2018), (D. Lauria, S et,al 2018) Saat ini, metode CP yang umum digunakan dalam struktur termasuk arus paksa perlindungan katodik (ICCP) dan anoda korban perlindungan katodik (SACP) (J. A. Jeong, et al., 2014)(K. Wilson,et al., 2013). ICCP adalah lebih cocok daripada SACP untuk aplikasi pada struktur besar dengan korosi yang signifikan dan penggunaan yang lebih panjang (K. Wilson, et al ,2013), dan ICCP adalah metode yang efektif untuk perlindungan korosi struktural dalam ion klorida lingkungan (G. Qiao, et al., 2017) (P. V. Bahekar and S. S. Gadve, 2017). Sistem ICCP memperlambat proses korosi dengan menyuntikkan arus ke dalam media sekitarnya untuk memodifikasi potensi permukaan struktur dan memastikan bahwa korosi proses berkurang (P.V.Bahekar and S. S. Gadve, et al 2019). (P. V. Bahekar, et al 2017) mengevaluasi efektivitas ICCP menggunakan setengah-sel metode potensial dan mengusulkan kepadatan arus proteksi yang sesuai untuk sistem ICCP. (Qiao et,al 2013) dan (Wang et,al 2018). (Wang et,al 2018) menggunakan simulasi numerik untuk mengoptimalkan sistem ICCP. (Christodoulou, et,al 2010) meneliti manfaat jangka panjang dari ICCP, dan hasilnya menunjukkan bahwa baja tetap pasif selama setidaknya 24 bulan setelah gangguan arus proteksi.

4.2 Metodologi Penelitian

4.2.1 Rancangan Penelitian

- a) Pengujian proteksi katodik ICCP secara auto pada sampel baja SS 303 menggunakan media air laut dengan salinitas 2,7 ‰; 3,1 ‰; dan 3,5 ‰ pada temperatur 38°C.
- b) Pengujian masing sampel SS 303 dengan metode:
 - Pengukuran potensial proteksi katodik.
 - Pengukuran kehilangan berat Sampel (*weight loss*)
 - SEM (*Scanning Electron Microscope*) dan EDS (*Energy Dispersive X-ray Spectroscopy*) FEG SEM Phenom Pharos RH, dengan metode Uji : ASTM E1508, parameter uji : Perbesaran 1000x

4.2.2 Bahan yang digunakan dalam penelitian ini adalah:

- a) Sampel baja tahan karat baja SS 303
- b) Sampel granit sebagai elektroda anoda
- c) Sampel elektroda referensi Ag/AgCl
- d) Air laut buatan menggunakan larutan NaCl dan Air Squades

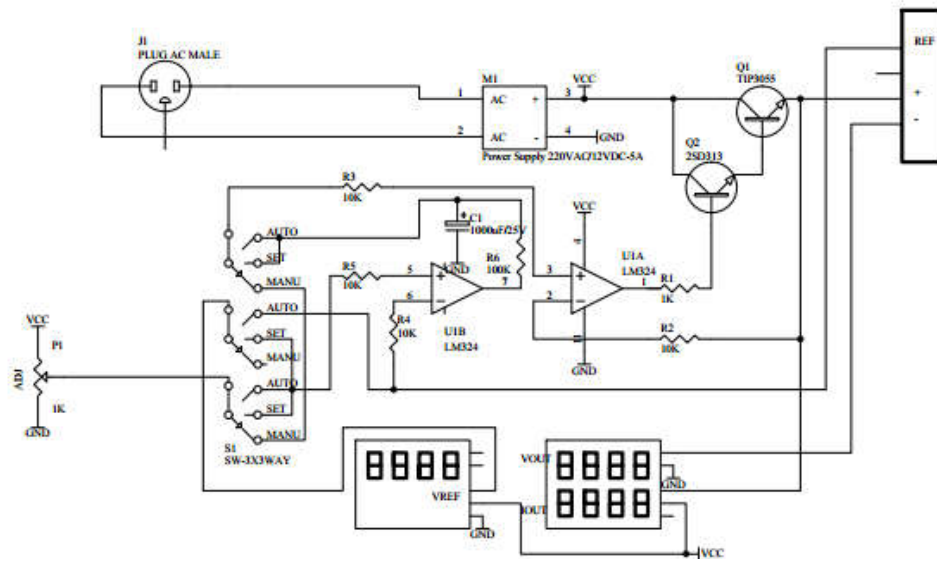
4.2.3 Alat yang digunakan dalam penelitian ini adalah:

- a) Multimeter Digital Sanwa Type CD 771
- b) Integrated Circuit (IC) LM 324
- c) Power supply 220 VAC/12 VDC-5A
- d) Transistor 2SD313
- e) Transistor TIP3055
- f) Kondensator 1000uF/25 V
- g) Resistor tetap 100 K
- h) Resistor tetap 10 K
- i) Seven Segmen Indikator
- j) Plug Jack male
- k) Switch SW 3 way

- l) Heater 50 Watt.
- m) Termometer Exact Instrument CT 3080
- n) Portable Refractometer
- o) Wadah Kotak Akrilic sebagai tempat media Air laut buatan.

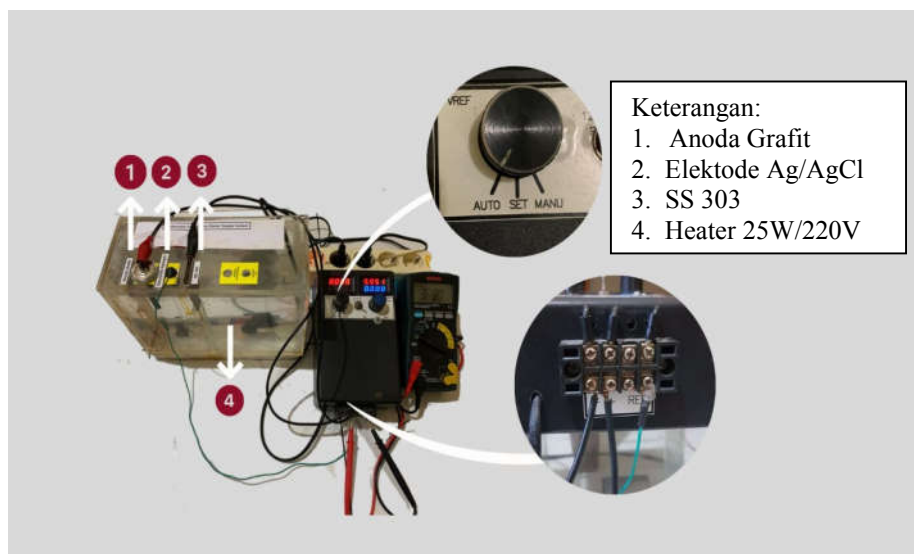
4.2.4 Rancangan Penelitian

a. Desain Sistem Proteksi Katodik Arus Paksa (*Impressed Current Cathodic Protection/ICCP*) Berbasis Manual Dan Auto



Gambar 4.1 Rangkaian impressed current cathodic protection berbasis auto

B. Pemasangan ICCP Auto Sebagai Katodik Proteksi Arus paksa



Gambar 4.2. Pemasangan ICCP auto pada Sampel SS 303

4.2.5 Media air laut buatan

Menggunakan larutan NaCl dan Air Aquades dengan ukuran sebagai berikut :

- a. salinitas 2,7 ‰. Ini berarti bahwa untuk setiap 1 liter (1000 mL) air aquades dan 2,7 gram NaCl
- b. salinitas 3,1 ‰. Ini berarti bahwa untuk setiap 1 liter (1000 mL) air aquades dan 3,1 gram NaCl
- c. salinitas 3,5 ‰. Ini berarti bahwa untuk setiap 1 liter (1000 mL) air aquades dan 3,5 gram NaCl

4.2.6 Prosedur Pengambilan Data

Dalam penelitian ini dilakukan sama dengan penelitian sebelumnya. Bedanya pengambilan data fokus menggunakan katodik proteksi ICCP yang sistem auto. Kemudian sampel di rendam secara bergantian di air laut buatan dengan tingkat salinitas yang berbeda-beda yaitu : 2,7 ‰; 3,1 ‰; dan 3,5 ‰. Perendaman sampel SS 303 selama 21 hari atau 504 jam dengan temperature 38°C. Setelah itu dilakukan pengukuran potensial sampel SS 303 yang direndam tanpa Proteksi Katodik ICCP, pengukuran potensial proteksi katodik ICCP secara manual dan auto pada sampel SS 303. Serta dilanjutkan dengan pengujian kehilangan berat (*weight loss*), lalu dilanjutkan pengujian SEM (*Scanning Electron Microscope*) dan EDS (*Energy Dispersive X-ray Spectroscopy*) FEG SEM Phenom Pharos RH, dengan metode Uji : ASTM E1508, parameter uji : Perbesaran 1000x.

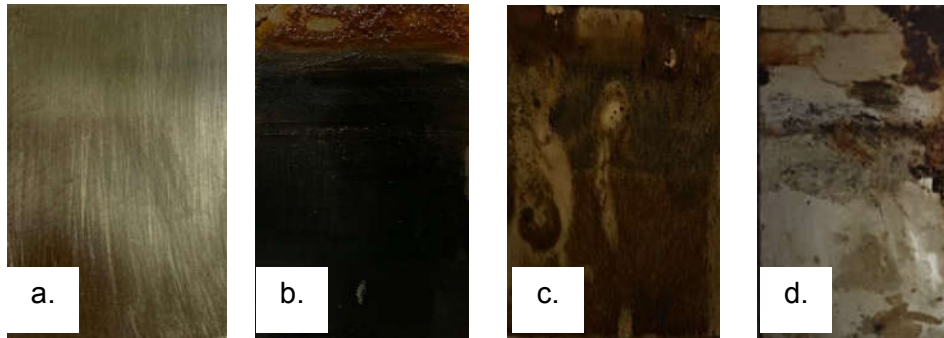
4.4 Hasil dan Pembahasan

Pengujian katodik proteksi arus paksa secara Auto terhadap sampel SS 303 dilakukan pada lingkungan air laut dengan indicator sebagai berikut :

- a) NaCl yang berbeda-beda yaitu 2,7 ‰; 3,1 ‰ dan 3,5 ‰.
- b) Temperatur 38° C

Pada **Gambar 4.3a** sampel SS 303 yang belum mendapat pengujian, kemudian **Gambar 4.3b** sampel SS 303 yang di uji pada NaCl 2,7 ‰ , sangat jelas perbedaan yang ditimbulkan akibat proses perendaman pada air laut buatan di

temperatur 38⁰ C. **Gambar 4.3c** Sampel direndam pada larutan NaCl 3.1 ‰ terlihat perubahan yang signifikan dari sebelumnya. Selanjutnya pada **gambar 4.3d** perubahan pada sampel yang direndam dilarutan NaCl 3.5 ‰.



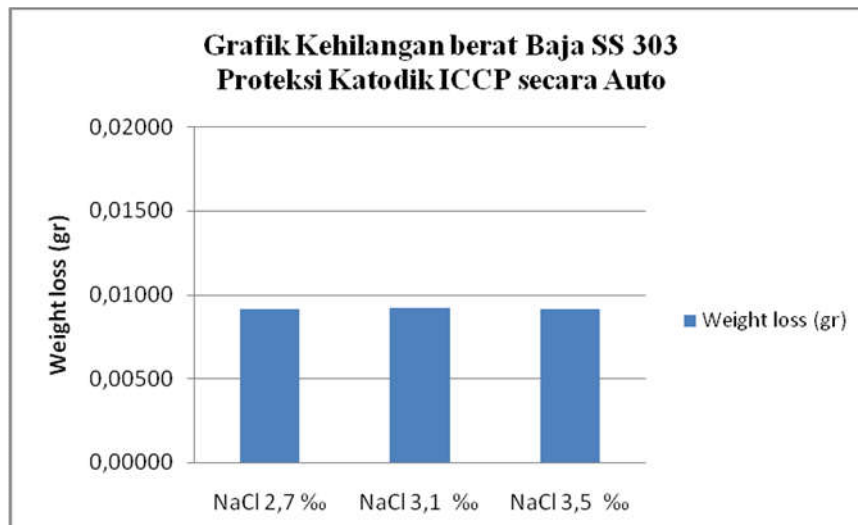
Gambar 4.3. Hasil pengujian Proteksi ICCP Auto pada sampel Baja SS 303, a) Sebelum pengujian, b) Pegujian pada NaCl 2,7 ‰, c) Pengujian pada NaCl 3,1 ‰, d) Pengujian pada NaCl 3.5 ‰.

B. Hasil pengujian Korosi

Pengujian korosi sampel SS 303 pada media air laut dengan temperature 38⁰C, NaCl 2,7 ‰; 3,1 ‰; dan 3,5 ‰ didapatkan hasil sebagai berikut : pada **tabel 4.1** terlihat perbedaan yang tidak signifikan dari 1 sampai 3, hanya sekitar 0.22 persen.

Tabel 4.1 Kehilangan berat sampel SS 303

No	Sampel SS 303	NaCl	Temperatur	Weight Loss
1	Pertama	2.7 ‰	38 ⁰ C	0,00915 gr
2	Kedua	3.1 ‰	38 ⁰ C	0,00919 gr
3	Ketiga	3.5 ‰	38 ⁰ C	0,00917 gr

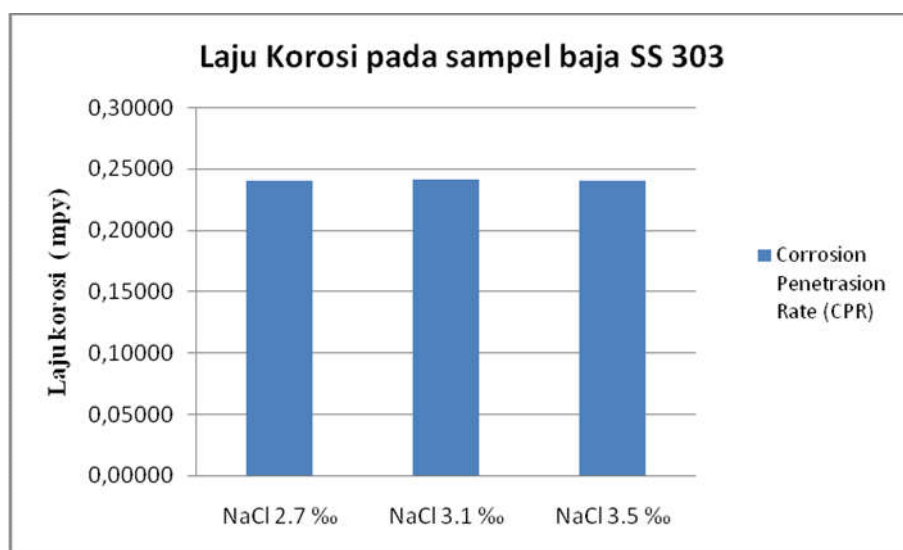


Gambar 4.4 Grafik Weight Loss pada sampel SS 303

Selanjutnya pada **tabel 4.2** menampilkan laju korosi pada sampel SS 303 melalui beberapa percobaan menggunakan proteksi katodik ICCP secara auto. Laju korosi sampel SS 303 yang direndam dalam percobaan 1 sampai 3 menunjukkan perbedaan sekitar 0,22 persen dari masing-masing percobaan.

Tabel 4.2 Laju Korosi SS 303 dengan proteksi katodik ICCP Auto

No	Sampel SS 303	NaCl	Temperatur	Laju Korosi
1	Pertama	2.7 ‰	38°C	0,24002 mpy
2	Kedua	3.1 ‰	38°C	0,24107 mpy
3	Ketiga	3.5 ‰	38°C	0,24055 mpy

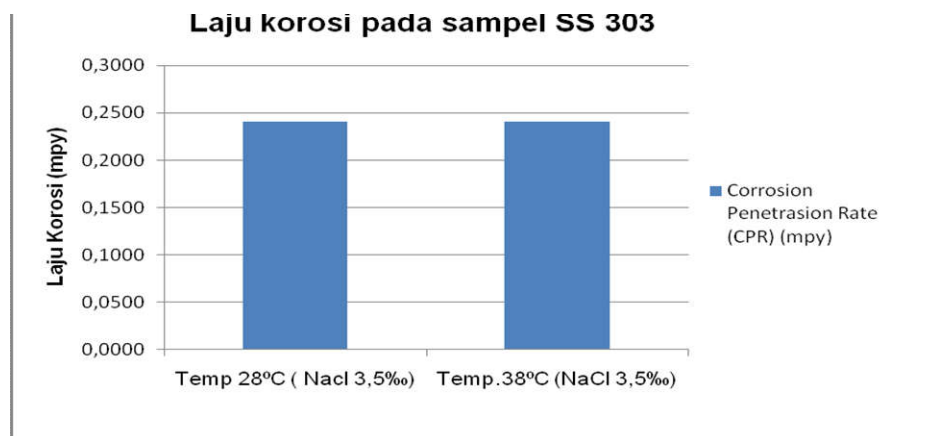


Gambar 4.5 Laju korosi baja SS 303 dengan proteksi katodik ICCP Auto

Dari tabel 4.1 dan gambar 4.2 terlihat laju korosi pada sampel SS 303, tidak mengalami perbedaan yang signifikan walaupun direndam dengan konsentrasi NaCl yang berbeda-beda. Hal tersebut diakibatkan oleh pengaruh proteksi katodik ICCP yang bekerja secara auto. Nilai potensial di kontrol pada daerah yang maksimal nilai $-0,800 V_{Ag/AgCl}$ sampai ambang batas minimal $-1,100 V_{Ag/AgCl}$. Sehingga laju korosi bisa dikendalikan secara maksimal.

Tabel 4.3 Laju Korosi SS 303 dengan proteksi katodik ICCP Auto

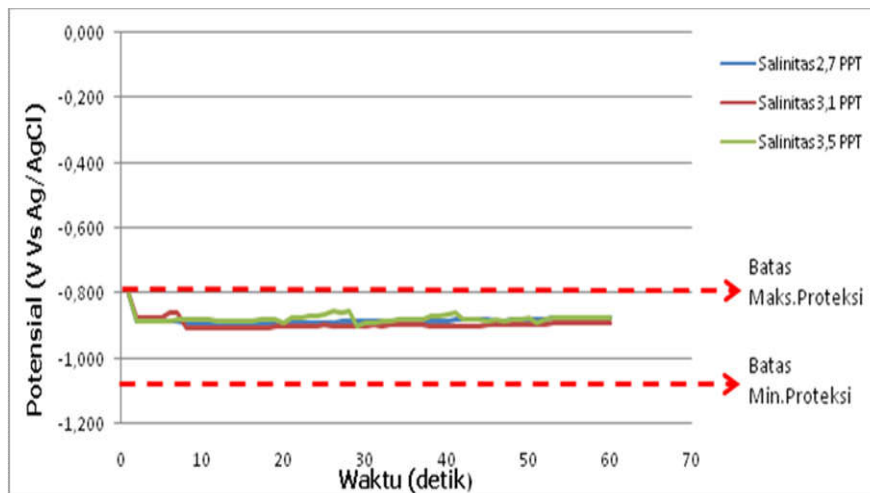
No	Sampel SS 303	NaCl	Temperatur	Laju Korosi
1	Pertama	3.5 ‰	28°C	0,24049 mpy
2	Kedua	3.5 ‰	38°C	0,24055 mpy



Gambar 4.6 Laju korosi SS 303 dengan temperatur yang berbeda

C. Pengujian Potensial sampel SS 303

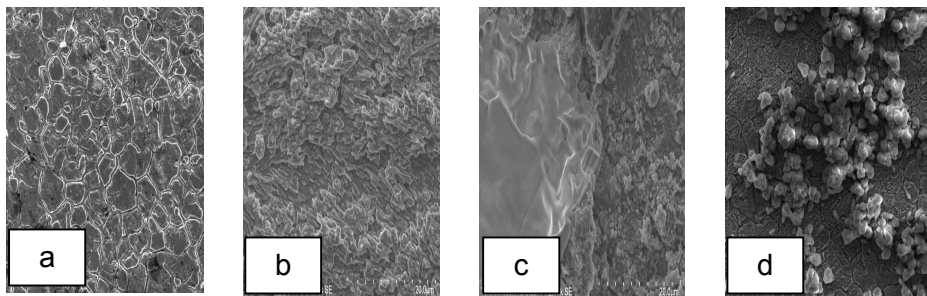
Nilai potensial untuk korosi dan perlindungan baja di lingkungan air laut menggunakan elektroda *reference* Ag/AgCl adalah berkisar minimal $-0,800 V_{Ag/AgCl}$ sampai dengan $-1,100 V_{Ag/AgCl}$. Jika lebih negatif dari $-1,100 V_{Ag/AgCl}$, maka akan menimbulkan ion hidroksi yaitu menghasilkan lingkungan yang sangat basah serta kandungan pH tinggi. Sehingga dapat menyebabkan dimulainya pelepasan katodik pada lapisan logam (Mahdavi, Forsyth, & Tan, 2016).



Gambar 4.7 Potensial SS 303 dengan ICCP Auto pada larutan NaCl 2,7 ‰; 3,1 ‰ dan 3,5 ‰

D. Pengujian *Scanning Electron Microscope* (SEM)

Pengujian SEM pada sampel SS 303 dilakukan untuk melihat struktur morfologi permukaan dan *crosssection* sampel dengan beberapa ukuran perbesaran.



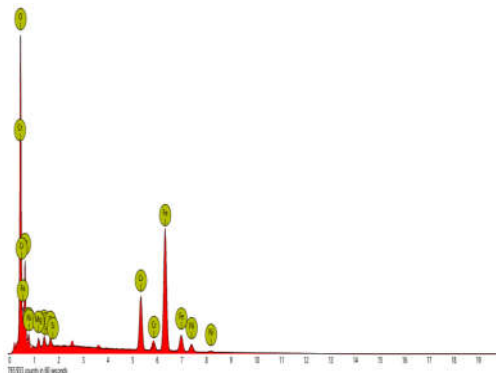
Gambar 4.8 Hasil pengujian SEM . a) Awal sampel; b) NaCl 2,7 ‰ c) 3,1 ‰; d) 3,5 ‰

Pada **Gambar 4.8** hasil pengujian untuk sampel SS 303 sebelum dan sesudah diproteksi katodik ICCP secara auto dengan lingkungan NaCl yang berbeda-beda yaitu 2,7 ‰; 3,1 ‰ dan 3,5 ‰, pada temperatur 38°C. Tampilan SEM yang dihasilkan dengan ukuran perbesaran 1000 X. Terlihat beberapa perbedaan antara sampel, **Gambar 4.8a** tampilan SEM untuk SS 303 sebelum mendapatkan uji proteksi katodik secara auto. **Gambar 4.8b** Tampilan uji SEM SS 303 yang diproteksi katodik secara auto di lingkungan NaCl 2,7 ‰. **Gambar**

4.8c Hasil Uji SEM SS 303 dengan proteksi katodik auto pada NaCl 3,1 ‰, **Gambar 4.8d** Tampilan uji SEM untuk sampel SS 303 setelah diproteksi katodik auto pada NaCl 3,5 ‰.

E. Pengujian *Energy Dispersive – X-Ray Spectroscopy* (EDS)

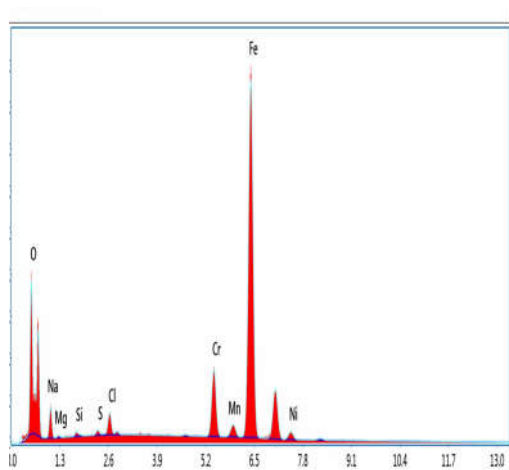
Pengujian EDS merupakan salah satu metode pengujian untuk menganalisa kandungan unsur-unsur kimia atau karakteristik pada material. Berdasarkan **gambar 4.9** terlihat unsur kimia yang terdapat pada material SS 303 sebelum direndam pada lingkungan air laut sintetis pada temperature 38°C serta NaCl yang berbeda-beda diantara NaCl 2,7 ‰, 3,1 ‰ dan 3,5 ‰ dengan perlakuan proteksi katodik ICCP secara auto.



Element Symbol	Element Name	Atomic Conc.	Weight Conc.
Fe	Iron	53.25	68.44
O	Oxygen	51.39	23.67
Cr	Chromium	9.02	13.50
Ni	Nickel	3.49	5.89
Br	Bromine	0.90	2.06
Mg	Magnesium	1.30	0.91
Si	Silicon	0.65	0.53

Gambar 4.9 Hasil EDS Sampel SS 303 Sebelum direndam

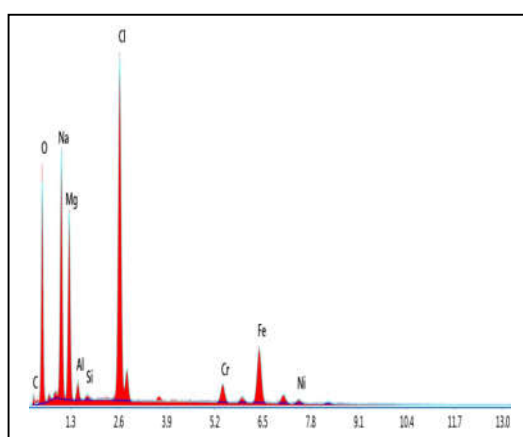
Pada **gambar 4.9** Tampilan hasil pengujian EDS sampel SS 303 sebelum direndam terlihat beberapa unsur kimia seperti besi (Fe), Oksigen (O), Krom (Cr), Nikel (Ni), Bromine (Br), Magnesium (Mg) dan silicon (Si). Adapun unsure yang sangat dominan pada SS 303 ini yaitu unsur besi sebesar 68,44 %. Unsur besi ini yang rentang terhadap korosi, sehingga melalui proteksi katodik ICCP secara auto diharapkan bisa mengendalikan laju korosi.



Element Symbol	Element Name	Atomic Conc.	Weight Conc.
O	Oxygen	23.94	9.31
Na	Natrium	12.69	7.09
Mg	Magnesium	0.48	0.28
Si	Silicon	0.52	0.36
S	Belerang	0.46	0.36
Cl	Klorin	1.68	1.45
Cr	Chromium	6.80	8.59
Mn	Mangan	0.57	0.76
Fe	Iron	51.28	69.57
Ni	Nickel	1.57	2.24

Gambar 4.10 Hasil EDS SS 303 pada NaCl 2,7 %

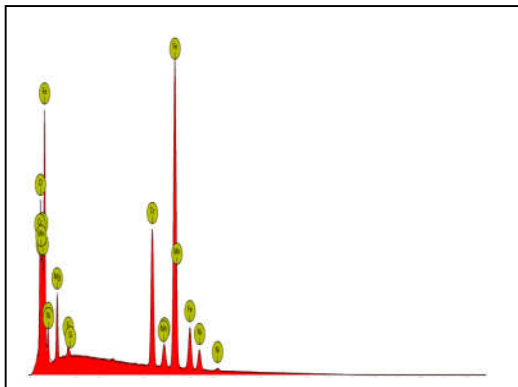
kimia diantaranya : Oksigen (O), Natrium (Na), Magnesium (Mg), Silicon (Si), Belerang (S), Klorin (Cl), Krom (Cr), Mangan (Mn), Besi atau Iron (Fe) dan Nikel (Ni). Salah produk korosi yang nilai berkurang adalah Oksigen, sebesar 23,94 % sehingga dengan berkurangnya jumlah oksigen yang terdapat pada material tersebut secara langsung berdampak bisa mengurangi laju korosi (Cao *et al.*, 2018)(Hou, Gao, Cui, & Yin, 2018). Kandungan unsur besi juga masih dalam jumlah yang besar sekitar 51,28 %, sehingga dari data EDS ini terlihat laju korosi bisa terkendali dengan baik.



Element Symbol	Element Name	Atomic Conc.	Weight Conc.
C	Karbon	4.41	1.88
O	Oxygen	24.37	35.48
Na	Natrium	22.04	22.33
Si	Silicon	0.31	0.26
Cl	Klorin	19.98	13.13
Cr	Chrom	2.46	1.10
Fe	Iron	10.30	4.22
Ni	Nickel	1.05	0.42

Gambar 4.11 Hasil EDS SS 303 pada NaCl 3,1 %

Pada **gambar 4.11** menampilkan hasil EDS memberikan informasi terkait unsur yang terkandung pada material SS 303 hasil proteksi katodik ICCP secara auto dalam air laut buatan dengan NaCl 3,1 ‰ serta temperatur 38°C yaitu unsure karbon (C), Oksigen (O), Natrium (Na), Silikon (Si), Klorin (Cl), Krom (Cr), Besi (Fe) dan Nikel (Ni).



Element Symbol	Element Name	Atomic Conc.	Weight Conc.
Fe	Iron	52.58	64.28
Cr	Chromium	14.44	16.44
Ni	Nickel	5.78	7.42
O	Oxygen	18.65	6.53
Mg	Magnesium	6.77	3.60
Mn	Mangan	1.07	1.29
Si	Silicon	0.71	0.44

Gambar 4.12 Hasil EDS SS 303 pada NaCl 3,5 ‰

Pada kondisi ini unsur oksigen masih dalam jumlah yang kurang lebih sama dengan kondisi NaCl 2,7 ‰ sebesar 24,37 %. Namun kandungan unsur besi yang jauh berkurang dari kondisi sebelumnya sebesar 10,30 %, jauh lebih kecil dibandingkan dengan percobaan pada NaCl 2,7 ‰.

Pada **gambar 4.12** menampilkan hasil EDS untuk sampel SS 303 yang direndam dalam air laut buatan dengan NaCl 3.5 ‰ dan di proteksi katodik ICCP secara auto. Unsur kimia yang terdeteksi adalah besi (Fe), Krom (Cr), Nikel (Ni), Oksigen (O), Magnesium (Mg), Mangan (Mn) dan Silikon (Si). Salah satu produk korosi yang berkurang yaitu Oksigen sebesar 18,65 %. Lebih kecil dibandingkan dengan kondisi sebelumnya baik pada NaCl 2,7 ‰ dan 3,1 ‰. Sehingga laju korosi pada material bisa lebih maksimal pengendaliannya. Berkurangnya unsur oksigen tersebut, maka proses penggetasan hydrogen ikut berkurang juga (*Meinhardt et al., 2017*).

4.5 Kesimpulan

Pengujian Proteksi katodik arus paksa (*impressed Current Cathodic Protection/ICCP*) secara Auto pada sampel SS 303 di lingkungan air laut buatan dengan kandungan NaCl 2,7 ‰; 3,1 ‰ dan 3,5 ‰ pada temperatur 38°C

Berdasarkan hasil penelitian, di dapatkan kesimpulan sebagai berikut :

- a. Pada pengujian kehilangan berat (weight loss) dari SS 303 melalui percobaan sebanyak 3 kali yaitu percobaan 1 sebesar 0,00915 gram. Percobaan 2 sebesar 0,00919 gram dan percobaan 3 sebesar 0,00917. Sehingga selisih dari masing-masing percobaan tersebut yaitu 0,22 persen.
- b. Pada pengujian laju korosi dihasilkan yaitu pada percobaan 1 sebesar 0,24002 mpy, percobaan ke-2 sebesar 0,24107 mpy dan percobaan ke-3 sebesar 0,24055 mpy. Selisih dari ke-3 percobaan tersebut yaitu 0,22 persen.
- c. Pada pengujian potensial proteksi didapatkan nilai potensial pada masing-masing percobaan antara -0,800 V/Ag/AgCl sampai dengan -1,100 V/Ag/AgCl. Termasuk dalam daerah terkendali laju korosinya.
- d. Pada pengujian *Scanning Electron Microscope* (SEM) dan *Energy Dispersive X-ray Spectroscopy* (EDS), terlihat salah satu produk korosi yaitu unsur oksigen (O) sebesar 23,94 pada percobaan pertama dengan kadar larutan NaCl 2,7 ‰. Pada percobaan ke-2 dengan kadar NaCl 3,1 ‰ didapatkan unsur oksigen (O) sebesar 24,37 persen dan pada kadar NaCl 3,5 ‰, unsur oksigen (O) sebesar 18,65 persen. Sangat jelas terlihat perbedaan yang signifikan.

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BAB V PEMBAHASAN UMUM

5.1 Percobaan 1. Pemetaan Current Density dan Kurva Polarisasi pada sampel Mild Steel (MS) 400 dan Stainless Steel (SS) 303 menggunakan pengujian sel tiga elektroda menggunakan larutan NaCl 2,7 ‰; 3,1 ‰ dan 3,5 ‰ pada temperatur 28°C dan 38°C.

Dalam percobaan ini melakukan pengujian polarisasi untuk mengetahui Pemetaan *Current Density* dan Kurva Polarisasi pada sampel SS 303 menggunakan pengujian sel tiga elektroda. Salinitas yang digunakan adalah menggunakan larutan NaCl 2,7 ‰; 3,1 ‰ dan 3,5 ‰ pada temperatur 28°C dan 38°C. Perubahan salinitas memiliki pengaruh yang besar terhadap laju pada *Mild Steel* (MS) 400 dan *Stainless Steel* (SS) 303. Tingkat salinitas (NaCl 3,5 ‰) yang sangat mempengaruhi laju korosi. Kemudian Laju korosi juga dipengaruhi oleh perubahan temperatur Hasil pengujian menunjukkan nilai arus korosi (I_{corr}) tertinggi pada temperatur 38°C dengan NaCl 3,5 ‰ sebesar 4.26×10^{-7} Amper untuk MS 400 dan SS 303 sebesar 1.32×10^{-6} Amper. Sedangkan Laju korosi *Stainless Steel* (SS) 303 sebesar 0,5851 mpy ,mempunyai ketahanan korosi yang lebih baik dari pada *Mild Steel* (MS) 400 dengan nilai laju korosi sebesar 0,6930 mpy. Karena pengaruh elemen paduan yang terkandung dalam baja SS 303

5.2 Percobaan 2. Sistem *Rectifier Direct Current* (DC) Secara Manual Dan Otomatis Untuk Proteksi Katodik Baja Tahan Karat (*Stainless Steel*) 303 Di Salinitas 3,5 ‰

Pada pengujian ini melakukan Proteksi katodik arus paksa (*impressed Current Cathodic Protection/ICCP*) secara manual dan Auto pada sampel SS 303 menggunakan media air laut buatan dengan kandungan NaCl 3.5 ‰ dengan kondisi temperatur 38°C. SS 303 mengalami perubahan berat (*Weight Loss*) sebesar 0,04339 gram tanpa perlakuan ICCP. Kondisi ini sampel mengalami kondisi terkorosi.

Kemudian menggunakan perlakuan ICCP secara manual dihasilkan *weight loss* sebesar 0,0325 gram. Kondisinya laju korosi lebih berkurang dibandingkan dengan tanpa menggunakan proteksi katodik. Sedangkan menggunakan proteksi ICCP secara Auto dihasilkan *weight loss* sebesar 0,00917 gram. Pada keadaan ini SS 303 mengalami perubahan yang lebih kecil dibandingkan dengan kondisi sebelumnya.

Laju korosi yang terjadi pada SS 303 melalui beberapa percobaan dihasilkan tanpa menggunakan ICCP sebesar 1,11828 *Mils Per Year* (mpy), menggunakan ICCP manual sebesar 0,83117 mpy dan menggunakan ICCP auto 0,24055 mpy.

Selanjutnya hasil Pengukuran potensial proteksi katodik pada spesimen SS 303 yang menggunakan ICCP auto selalu berada di area negatif $-0,800 \text{ mV}_{\text{Ag/AgCl}}$ hingga $-1100 \text{ mV}_{\text{Ag/AgCl}}$ sehingga material logam SS 303 dapat terproteksi dengan baik sehingga laju korosi bisa dikendalikan dengan baik. Kemudian untuk melihat morfologi dari SS 303 dilakukan Pengujian *Scanning Electron Microscope* (SEM) dan *Energy Dispersive X-ray Spectroscopy* (EDS) terlihat unsur oksigen (O) yang relatif lebih kecil sebesar 6,53 % pada spesimen SS 303 yang terlindungi dengan ICCP auto, dibandingkan dengan SS 303 yang menggunakan perlindungan ICCP manual sebesar 21,77 %. Dimana unsur oksigen ini merupakan salah satu produk yang dapat menimbulkan terjadinya peningkatan korosi. Sehingga akan memcepat usia dari material yang digunakan.

5.3 Percobaan 3. Sistem *Rectifier Direct Current* (DC) Secara Otomatis Untuk Proteksi Katodik Baja Tahan Karat (*Stainless Steel*) 303 pada Larutan NaCl 2,7 ‰; 3,1 ‰ dan 3,5 ‰.

Pada percobaan ini dilakukan pengujian Proteksi katodik arus paksa (*impressed Current Cathodic Protection/ICCP*) secara Auto pada sampel SS 303 di lingkungan air laut buatan dengan kandungan NaCl 2,7 ‰; 3,1 ‰ dan 3,5 ‰ pada temperature 38°C. Hasil percobaan tersebut didapatkan beberapa hasil yaitu pengujian kehilangan berat (*weight loss*) dari SS 303 melalui percobaan sebanyak 3 kali yaitu percobaan 1 sebesar 0,00915 gram. Percobaan 2 sebesar 0,00919 gram dan

percobaan 3 sebesar 0,00917. Sehingga selisih dari masing-masing percobaan tersebut yaitu 0,22 persen.

Kemudian dilanjutkan dengan pengujian laju korosi dihasilkan yaitu pada percobaan 1 sebesar 0,24002 mpy, percobaan ke-2 sebesar 0,24107 mpy dan percobaan ke-3 sebesar 0,24055 mpy. Selisih dari ke-3 percobaan tersebut yaitu 0,22 persen. Lalu berikutnya pada potensial proteksi di dapatkan nilai potensial pada masing-masing percobaan antara $-0,800 \text{ mV}/_{\text{Ag}/\text{AgCl}}$ sampai dengan $-1,100 \text{ mV}/_{\text{Ag}/\text{AgCl}}$. Termasuk dalam daerah terkendali laju korosinya.

Selanjutnya dilakukan pengujian *Scanning Electron Microscope* (SEM) untuk melihat morfologi dari sampel SS 303 dan *Energy Dispersive X-ray Spectroscopy* (EDS), terlihat salah satu produk korosi yaitu unsur oksigen (O) sebesar 23,94 pada percobaan pertama dengan kadar larutan NaCl 2,7 ‰. Pada percobaan ke-2 dengan kadar NaCl 3,1 ‰ didapatkan unsur oksigen (O) sebesar 24,37 persen dan pada kadar NaCl 3,5 ‰, unsur oksigen (O) sebesar 18,65 persen. Sangat jelas terlihat perbedaan sebesar, melalui proteksi katodik ICCP secara auto diharapkan kandungan unsur Oksigen bisa lebih berkurang sehingga bisa menghindari terjadinya penggetasan pada material.

BAB VI KESIMPULAN UMUM

Setelah melakukan penelitian ini sebanyak 3 kali percobaan, maka dapat disimpulkan sebagai berikut :

1. Material logam merupakan bahan yang mudah mengalami korosi pada lingkungan yang mengandung air. Pada saat logam terkena air maka karbon di udara, sehingga asam karbonat akan terbentuk. Mengakibatkan unsur besi pada logam akan menjadi larut. Hidrogen dan oksigen akan terurai pada sebagian air.
2. Air Laut yang mengandung unsur garam, dapat meningkatkan laju korosi pada material logam. Semakin tinggi kandungan NaCl maka, laju korosi semakin meningkat. Sehingga perlu dilakukan sebuah metode pengendalian laju korosi salah satunya dengan proteksi katodik menggunakan arus listrik dari bantuan sistem rectifier.
3. Proteksi Impressed Current Cathodic Protection (ICCP) menggunakan sistem Rectifier Direct Current (DC) secara auto, sangat membantu dalam mengendalikan laju korosi pada baja paduan.

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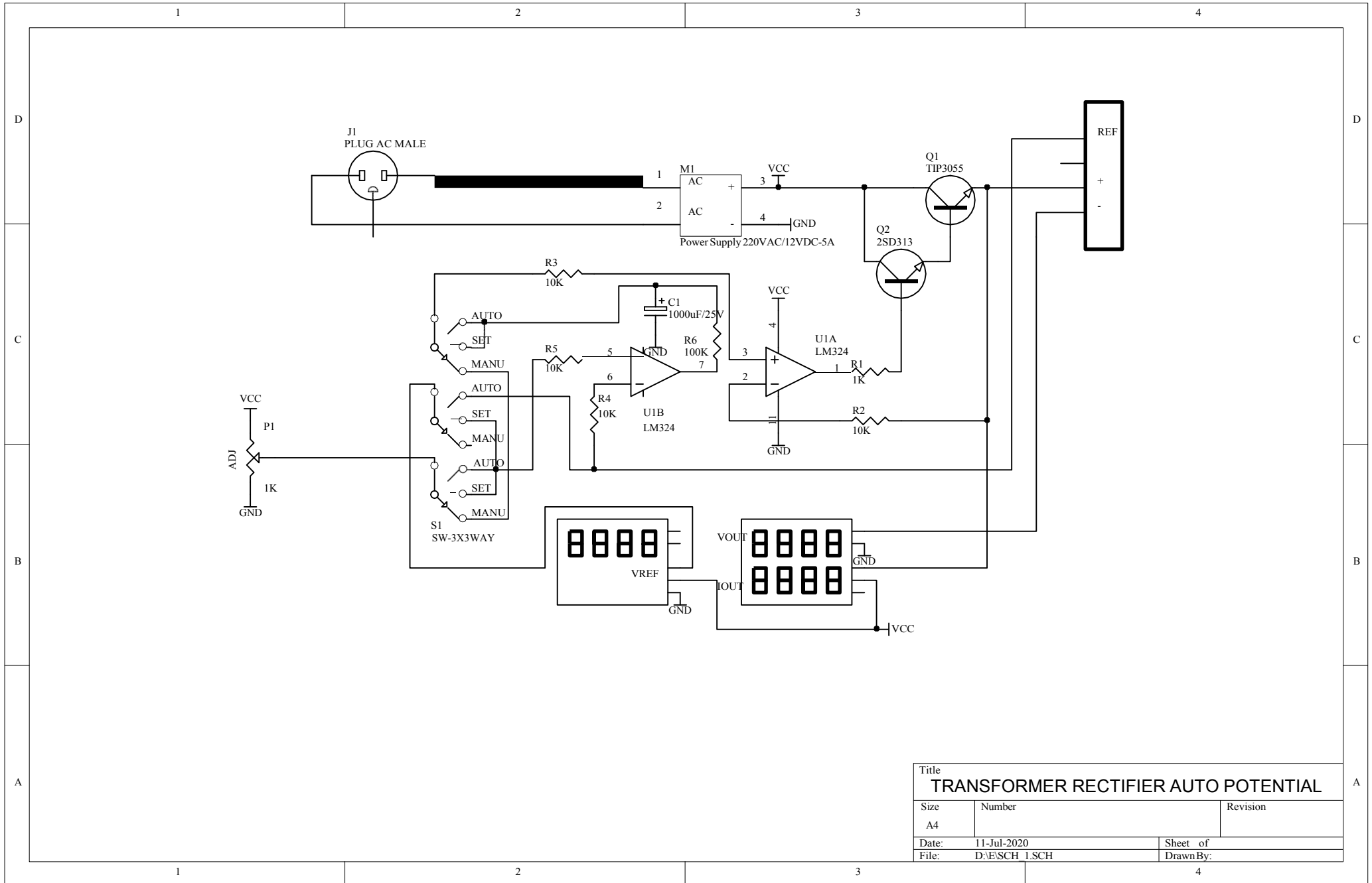
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Lampiran 1. Rangkaian *Rectifier Auto*



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TRANSFORMER RECTIFIER AUTO POTENTIAL		
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Lampiran 2 *Chemical result Stainless Steel (SS) 303*

FMX 52V0001 Optik 52V0041

Sample :SS 303

SS 303 : FE_150 Mode : PA 26/11/2020 11:54:34

	Fe	C	Si	Mn	P	S	Cr
1	73.3	0.0920	0.435	1.89	< 0.0015	< 0.0010	> 6.00
2	73.0	0.0955	0.392	1.94	< 0.0015	< 0.0010	> 6.00
3	73.3	0.0900	0.433	1.96	< 0.0015	< 0.0010	> 6.00
Average	73.2	0.0925	0.420	1.93	< 0.0015	< 0.0010	> 6.00

	Mo	Ni	Al	Co	Cu	Nb	Ti
1	0.0338	> 6.00	0.0012	0.165	0.0191	0.0012	< 0.0002
2	0.0331	> 6.00	< 0.0010	0.169	0.0192	0.0016	< 0.0002
3	0.0332	> 6.00	< 0.0010	0.173	0.0192	0.0052	< 0.0002
Average	0.0334	> 6.00	< 0.0010	0.169	0.0192	0.0027	< 0.0002

	V	W	Pb	Sn	B	Zr	Zn
1	0.110	< 0.0100	0.0358	< 0.0010	< 0.0004	< 0.0005	> 0.0200
2	0.109	< 0.0100	0.0337	0.0012	< 0.0004	< 0.0005	> 0.0200
3	0.110	< 0.0100	0.0388	< 0.0010	< 0.0004	< 0.0005	> 0.0200
Average	0.110	< 0.0100	0.0361	< 0.0010	< 0.0004	< 0.0005	> 0.0200

	Bi	As	Se	Sb
1	0.0114	0.0556	0.0185	0.0498
2	0.0126	0.0590	0.0178	< 0.0030
3	0.0115	0.0653	0.0170	< 0.0030
Average	0.0118	0.0600	0.0178	0.0166

Lampiran 3 Chemical result Mild Steel (MS) 400

Oxford Instruments Analytical GmbH Sample Testing of different Qualities Chemical Results

Probe Nr. / sample ID : ASTM A4852	Grundwerkstoff / material : Fe
Kunde / customer : SS 400	Abmessung / dimension :
Kom.-Nr. / commission :	Zusatzwerkstoff / filler metals :
Labor Nr. / lab-no. : Salim	Wärmebehandlung / heat treatment : No
PTQ-Nr. / PTQ-no. :	Schmelze-Nr. / heat-no. :

Spektralanalyse FMX Werkstoff / grade :

	Fe	C	Si	Mn	P	S	Cr	Mo
1	99.0	0.100	0.139	0.329	< 0.0015	< 0.0010	0.0964	0.0083
2	99.0	0.0978	0.148	0.332	< 0.0015	< 0.0010	0.104	0.0085
3	96.2	0.206	0.120	0.300	< 0.0015	0.0096	0.0970	0.0149
Ave	98.1	0.135	0.135	0.320	< 0.0015	0.0032	0.0991	0.0106

	Ni	Al	Co	Cu	Nb	Ti	V	W
1	0.0506	0.0172	0.0062	0.113	< 0.0005	0.0028	< 0.0005	0.0175
2	0.0494	0.0187	0.0066	0.117	< 0.0005	0.0027	0.0009	< 0.0100
3	0.0446	0.0367	< 0.0010	0.0998	0.0033	0.0044	0.0035	0.0687
Ave	0.0482	0.0242	0.0045	0.110	0.0011	0.0033	0.0015	0.0287

	Pb	Sn	B	Ca	Zr	Zn	Bi	As
1	0.0016	0.0109	< 0.0004	> 0.0080	< 0.0005	0.0013	0.0148	0.0067
2	0.0022	0.0109	< 0.0004	> 0.0080	< 0.0005	0.0019	0.0156	0.0043
3	0.0215	0.157	0.0199	> 0.0080	< 0.0005	> 0.0200	0.0153	> 0.100
Ave	0.0084	0.0594	0.0066	> 0.0080	< 0.0005	> 0.0200	0.0152	0.0710

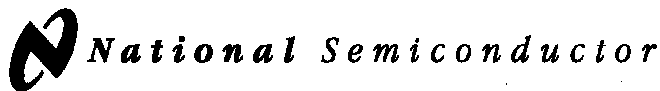
	Se	Sb
1	0.0145	0.0118
2	0.0126	0.0082
3	> 0.0500	> 0.100
Ave	> 0.0500	> 0.100

Ort / town	Datum / date	Prüfer / tester	Sachverständiger / engineer
	26/11/2020		

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Lampiran 4. Luaran Penelitian

No	Judul	Authors	Jurnal	Status
1	Uppression Of Corrosion On Stainless Steel 303 With Automatic Impressed Current Cathodic Protection (A-Iccp) Method In Simulated Seawater	Hamsir Onny Sutresrman Hairul Arsyad Muhammad Syahid Agus Widyianto	Journal of Enterprise Technologies. (Scopus, Q2, h index 9)	Published date 29.12.2022 Journal of Enterprise Technologies, 6 (12 (120)), 13–21. doi: https://doi.org/10.15587/1729-4061.2022.267264



March 2000

LM124/LM224/LM324/LM2902 Low Power Quad Operational Amplifiers

General Description

The LM124 series consists of four independent, high gain, internally frequency compensated operational amplifiers which were designed specifically to operate from a single power supply over a wide range of voltages. Operation from split power supplies is also possible and the low power supply current drain is independent of the magnitude of the power supply voltage.

Application areas include transducer amplifiers, DC gain blocks and all the conventional op amp circuits which now can be more easily implemented in single power supply systems. For example, the LM124 series can be directly operated off of the standard +5V power supply voltage which is used in digital systems and will easily provide the required interface electronics without requiring the additional $\pm 15V$ power supplies.

Unique Characteristics

- n In the linear mode the input common-mode voltage range includes ground and the output voltage can also swing to ground, even though operated from only a single power supply voltage
- n The unity gain cross frequency is temperature compensated
- n The input bias current is also temperature compensated

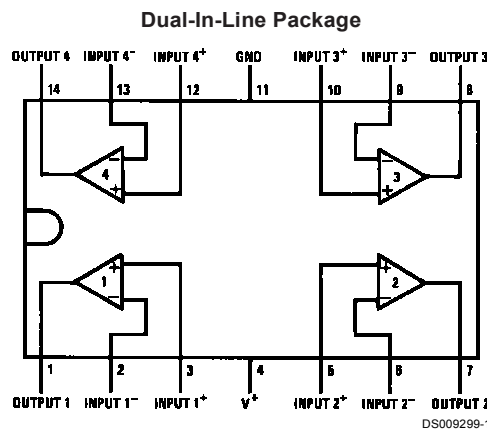
Advantages

- n Eliminates need for dual supplies
- n Four internally compensated op amps in a single package
- n Allows directly sensing near GND and V_{OUT} also goes to GND
- n Compatible with all forms of logic
- n Power drain suitable for battery operation

Features

- n Internally frequency compensated for unity gain
- n Large DC voltage gain 100 dB
- n Wide bandwidth (unity gain) 1 MHz (temperature compensated)
- n Wide power supply range:
 - Single supply 3V to 32V
 - or dual supplies $\pm 1.5V$ to $\pm 16V$
- n Very low supply current drain (700 μA) — essentially independent of supply voltage
- n Low input biasing current 45 nA (temperature compensated)
- n Low input offset voltage 2 mV and offset current: 5 nA
- n Input common-mode voltage range includes ground
- n Differential input voltage range equal to the power supply voltage
- n Large output voltage swing 0V to $V^+ - 1.5V$

Connection Diagram



Top View

Order Number LM124J, LM124AJ, LM124J/883 (Note 2), LM124AJ/883 (Note 1), LM224J, LM224AJ, LM324J, LM324M, LM324AM, LM2902M, LM324N, LM324AN, LM324MT, LM324MTX or LM2902N LM124AJRQML and LM124AJRQMLV (Note 3)
See NS Package Number J14A, M14A or N14A

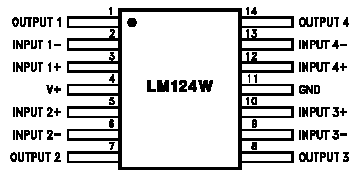
Note 1: LM124A available per JM38510/11006

Note 2: LM124 available per JM38510/11005

Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

Connection Diagram (Continued)

Note 3: See STD Mil DWG 5962R99504 for Radiation Tolerant Device



DS009299-33

Order Number LM124AW/883 or LM124W/883
 LM124AWRQML and LM124AWRQMLV(Note 3)
 See NS Package Number W14B
 LM124AWGRQML and LM124AWGRQMLV(Note 3)
 See NS Package Number WG14A

Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

LM124/LM224/LM324/LM2902

Absolute Maximum Ratings (Note 12)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/Distributors for availability and specifications.

	LM124/LM224/LM324 LM124A/LM224A/LM324A	LM2902
	Supply Voltage, V^+	32V
Differential Input Voltage	32V	26V
Input Voltage	-0.3V to +32V	-0.3V to +26V
Input Current ($V_{IN} < -0.3V$) (Note 6)	50 mA	50 mA
Power Dissipation (Note 4)		
Molded DIP	1130 mW	1130 mW
Cavity DIP	1260 mW	1260 mW
Small Outline Package	800 mW	800 mW
Output Short-Circuit to GND (One Amplifier) (Note 5) $V^+ \leq 15V$ and $T_A = 25^\circ C$	Continuous	Continuous
Operating Temperature Range		-40°C to +85°C
LM324/LM324A	0°C to +70°C	
LM224/LM224A	-25°C to +85°C	
LM124/LM124A	-55°C to +125°C	
Storage Temperature Range	-65°C to +150°C	-65°C to +150°C
Lead Temperature (Soldering, 10 seconds)	260°C	260°C
Soldering Information		
Dual-In-Line Package		
Soldering (10 seconds)	260°C	260°C
Small Outline Package		
Vapor Phase (60 seconds)	215°C	215°C
Infrared (15 seconds)	220°C	220°C
See AN-450 "Surface Mounting Methods and Their Effect on Product Reliability" for other methods of soldering surface mount devices.		
ESD Tolerance (Note 13)	250V	250V

Electrical Characteristics

$V^+ = +5.0V$, (Note 7), unless otherwise stated

Parameter	Conditions	LM124A			LM224A			LM324A			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	(Note 8) $T_A = 25^\circ C$		1	2		1	3		2	3	mV
Input Bias Current (Note 9)	$I_{IN(+)}$ or $I_{IN(-)}$, $V_{CM} = 0V$, $T_A = 25^\circ C$		20	50		40	80		45	100	nA
Input Offset Current	$I_{IN(+)}$ or $I_{IN(-)}$, $V_{CM} = 0V$, $T_A = 25^\circ C$		2	10		2	15		5	30	nA
Input Common-Mode Voltage Range (Note 10)	$V^+ = 30V$, (LM2902, $V^+ = 26V$), $T_A = 25^\circ C$	0		$V^+ - 1.5$	0		$V^+ - 1.5$	0		$V^+ - 1.5$	V
Supply Current	Over Full Temperature Range $R_L = \infty$ On All Op Amps $V^+ = 30V$ (LM2902 $V^+ = 26V$) $V^+ = 5V$		1.5	3		1.5	3		1.5	3	mA
			0.7	1.2		0.7	1.2		0.7	1.2	
Large Signal Voltage Gain	$V^+ = 15V$, $R_L \geq 2k\Omega$, ($V_O = 1V$ to $11V$), $T_A = 25^\circ C$	50	100		50	100		25	100		V/mV
Common-Mode Rejection Ratio	DC, $V_{CM} = 0V$ to $V^+ - 1.5V$, $T_A = 25^\circ C$	70	85		70	85		65	85		dB

Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

Electrical Characteristics (Continued)

V⁺ = +5.0V, (Note 7), unless otherwise stated

Parameter	Conditions	LM124A			LM224A			LM324A			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Power Supply Rejection Ratio	V ⁺ = 5V to 30V (LM2902, V ⁺ = 5V to 26V), T _A = 25°C	65	100		65	100		65	100		dB
Amplifier-to-Amplifier Coupling (Note 11)	f = 1 kHz to 20 kHz, T _A = 25°C (Input Referred)			-120			-120			-120	dB
Output Current	Source V _{IN⁺} = 1V, V _{IN⁻} = 0V, V ⁺ = 15V, V _O = 2V, T _A = 25°C	20	40		20	40		20	40		mA
	Sink V _{IN⁻} = 1V, V _{IN⁺} = 0V, V ⁺ = 15V, V _O = 2V, T _A = 25°C	10	20		10	20		10	20		
	Sink V _{IN⁻} = 1V, V _{IN⁺} = 0V, V ⁺ = 15V, V _O = 200 mV, T _A = 25°C	12	50		12	50		12	50		μA
Short Circuit to Ground	(Note 5) V ⁺ = 15V, T _A = 25°C		40	60		40	60		40	60	mA
Input Offset Voltage	(Note 8)			4			4			5	mV
Input Offset Voltage Drift	R _S = 0Ω		7	20		7	20		7	30	μV/°C
Input Offset Current	I _{IN(+)} - I _{IN(-)} , V _{CM} = 0V			30			30			75	nA
Input Offset Current Drift	R _S = 0Ω		10	200		10	200		10	300	pA/°C
Input Bias Current	I _{IN(+)} or I _{IN(-)}		40	100		40	100		40	200	nA
Input Common-Mode Voltage Range (Note 10)	V ⁺ = +30V (LM2902, V ⁺ = 26V)	0		V ⁺ -2	0		V ⁺ -2	0		V ⁺ -2	V
Large Signal Voltage Gain	V ⁺ = +15V (V _O Swing = 1V to 11V) R _L ≥ 2 kΩ	25			25			15			V/mV
Output Voltage Swing	V _{OH} V ⁺ = 30V (LM2902, V ⁺ = 26V)		26		26		26		26		V
	V _{OL} V ⁺ = 5V, R _L = 10 kΩ		5	20		5	20		5	20	mV
Output Current	Source V _O = 2V V _{IN⁺} = +1V, V _{IN⁻} = 0V, V _{IN⁺} = 15V	10	20		10	20		10	20		mA
	Sink V _{IN⁻} = +1V, V _{IN⁺} = 0V, V _{IN⁻} = 15V	10	15		5	8		5	8		

Electrical Characteristics

V⁺ = +5.0V, (Note 7), unless otherwise stated

Parameter	Conditions	LM124/LM224			LM324			LM2902			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	(Note 8) T _A = 25°C		2	5		2	7		2	7	mV
Input Bias Current (Note 9)	I _{IN(+)} or I _{IN(-)} , V _{CM} = 0V, T _A = 25°C		45	150		45	250		45	250	nA
Input Offset Current	I _{IN(+)} or I _{IN(-)} , V _{CM} = 0V, T _A = 25°C		3	30		5	50		5	50	nA
Input Common-Mode Voltage Range (Note 10)	V ⁺ = 30V, (LM2902, V ⁺ = 26V), T _A = 25°C	0		V ⁺ -1.5	0		V ⁺ -1.5	0		V ⁺ -1.5	V
Supply Current	Over Full Temperature Range R _L = ∞ On All Op Amps V ⁺ = 30V (LM2902 V ⁺ = 26V) V ⁺ = 5V		1.5	3		1.5	3		1.5	3	mA
			0.7	1.2		0.7	1.2		0.7	1.2	
Large Signal Voltage Gain	V ⁺ = 15V, R _L ≥ 2kΩ, (V _O = 1V to 11V), T _A = 25°C	50	100		25	100		25	100		V/mV

Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

Electrical Characteristics (Continued)

$V^+ = +5.0V$, (Note 7), unless otherwise stated

Parameter		Conditions	LM124/LM224			LM324			LM2902			Units
			Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Common-Mode Rejection Ratio		DC, $V_{CM} = 0V$ to $V^+ - 1.5V$, $T_A = 25^\circ C$	70	85		65	85		50	70		dB
Power Supply Rejection Ratio		$V^+ = 5V$ to $30V$ (LM2902, $V^+ = 5V$ to $26V$), $T_A = 25^\circ C$	65	100		65	100		50	100		dB
Amplifier-to-Amplifier Coupling (Note 11)		$f = 1$ kHz to 20 kHz, $T_A = 25^\circ C$ (Input Referred)	-120			-120			-120			dB
Output Current	Source	$V_{IN}^+ = 1V$, $V_{IN}^- = 0V$, $V^+ = 15V$, $V_O = 2V$, $T_A = 25^\circ C$	20	40		20	40		20	40		mA
	Sink	$V_{IN}^- = 1V$, $V_{IN}^+ = 0V$, $V^+ = 15V$, $V_O = 2V$, $T_A = 25^\circ C$	10	20		10	20		10	20		
		$V_{IN}^- = 1V$, $V_{IN}^+ = 0V$, $V^+ = 15V$, $V_O = 200$ mV, $T_A = 25^\circ C$	12	50		12	50		12	50		μA
Short Circuit to Ground		(Note 5) $V^+ = 15V$, $T_A = 25^\circ C$	40		60	40		60	40		60	mA
Input Offset Voltage		(Note 8)	7			9			10			mV
Input Offset Voltage Drift		$R_S = 0\Omega$	7			7			7			$\mu V/^\circ C$
Input Offset Current		$I_{IN(+)} - I_{IN(-)}$, $V_{CM} = 0V$	100			150			45		200	nA
Input Offset Current Drift		$R_S = 0\Omega$	10			10			10			$pA/^\circ C$
Input Bias Current		$I_{IN(+)} \text{ or } I_{IN(-)}$	40		300	40		500	40		500	nA
Input Common-Mode Voltage Range (Note 10)		$V^+ = +30V$ (LM2902, $V^+ = 26V$)	0		$V^+ - 2$	0		$V^+ - 2$	0		$V^+ - 2$	V
Large Signal Voltage Gain		$V^+ = +15V$ (V_O Swing = $1V$ to $11V$) $R_L \geq 2$ k Ω	25			15			15			V/mV
Output Voltage Swing	V_{OH}	$V^+ = 30V$ (LM2902, $V^+ = 26V$)	$R_L = 2$ k Ω		26	26		22				V
			$R_L = 10$ k Ω		27	28	27	28	23	24		
	V_{OL}	$V^+ = 5V$, $R_L = 10$ k Ω	5		20	5		20	5		100	mV
Output Current	Source	$V_O = 2V$	$V_{IN}^+ = +1V$, $V_{IN}^- = 0V$, $V^+ = 15V$		10	20	10	20	10	20		mA
	Sink		$V_{IN}^- = +1V$, $V_{IN}^+ = 0V$, $V^+ = 15V$		5	8	5	8	5	8		

Note 4: For operating at high temperatures, the LM324/LM324A/LM2902 must be derated based on a $+125^\circ C$ maximum junction temperature and a thermal resistance of $88^\circ C/W$ which applies for the device soldered in a printed circuit board, operating in a still air ambient. The LM224/LM224A and LM124/LM124A can be derated based on a $+150^\circ C$ maximum junction temperature. The dissipation is the total of all four amplifiers — use external resistors, where possible, to allow the amplifier to saturate or to reduce the power which is dissipated in the integrated circuit.

Note 5: Short circuits from the output to V^+ can cause excessive heating and eventual destruction. When considering short circuits to ground, the maximum output current is approximately 40 mA independent of the magnitude of V^+ . At values of supply voltage in excess of $+15V$, continuous short-circuits can exceed the power dissipation ratings and cause eventual destruction. Destructive dissipation can result from simultaneous shorts on all amplifiers.

Note 6: This input current will only exist when the voltage at any of the input leads is driven negative. It is due to the collector-base junction of the input PNP transistors becoming forward biased and thereby acting as input diode clamps. In addition to this diode action, there is also lateral NPN parasitic transistor action on the IC chip. This transistor action can cause the output voltages of the op amps to go to the V^+ voltage level (or to ground for a large overdrive) for the time duration that an input is driven negative. This is not destructive and normal output states will re-establish when the input voltage, which was negative, again returns to a value greater than $-0.3V$ (at $25^\circ C$).

Note 7: These specifications are limited to $-55^\circ C \leq T_A \leq +125^\circ C$ for the LM124/LM124A. With the LM224/LM224A, all temperature specifications are limited to $-25^\circ C \leq T_A \leq +85^\circ C$, the LM324/LM324A temperature specifications are limited to $0^\circ C \leq T_A \leq +70^\circ C$, and the LM2902 specifications are limited to $-40^\circ C \leq T_A \leq +85^\circ C$.

Note 8: $V_O \geq 1.4V$, $R_S = 0\Omega$ with V^+ from $5V$ to $30V$; and over the full input common-mode range ($0V$ to $V^+ - 1.5V$) for LM2902, V^+ from $5V$ to $26V$.

Note 9: The direction of the input current is out of the IC due to the PNP input stage. This current is essentially constant, independent of the state of the output so no loading change exists on the input lines.

Note 10: The input common-mode voltage of either input signal voltage should not be allowed to go negative by more than $0.3V$ (at $25^\circ C$). The upper end of the common-mode voltage range is $V^+ - 1.5V$ (at $25^\circ C$), but either or both inputs can go to $+32V$ without damage ($+26V$ for LM2902), independent of the magnitude of V^+ .

Note 11: Due to proximity of external components, insure that coupling is not originating via stray capacitance between these external parts. This typically can be detected as this type of capacitance increases at higher frequencies.

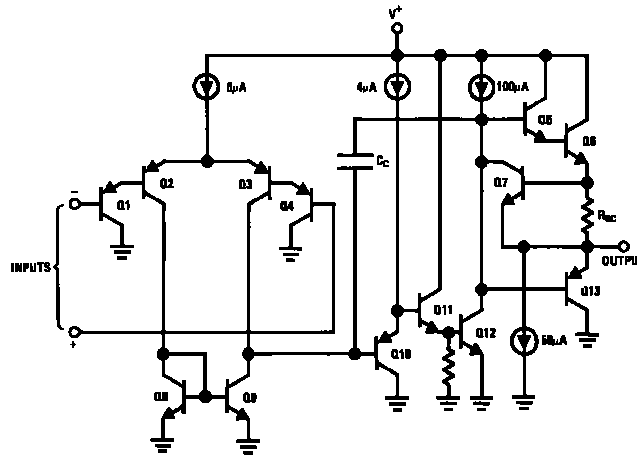
Note 12: Refer to RETS124AX for LM124A military specifications and refer to RETS124X for LM124 military specifications.

Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

Electrical Characteristics (Continued)

Note 13: Human body model, 1.5 kΩ in series with 100 pF.

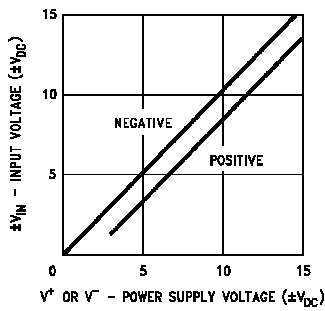
Schematic Diagram (Each Amplifier)



DS009299-2

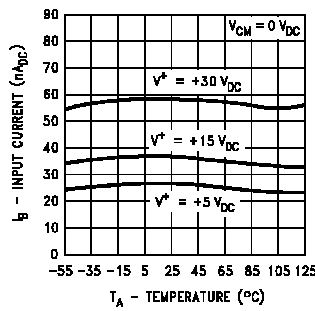
Typical Performance Characteristics

Input Voltage Range



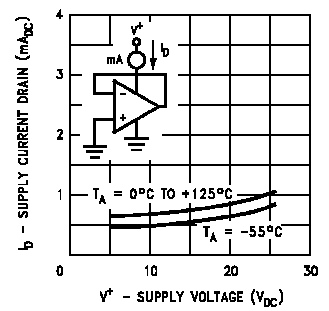
DS009299-34

Input Current



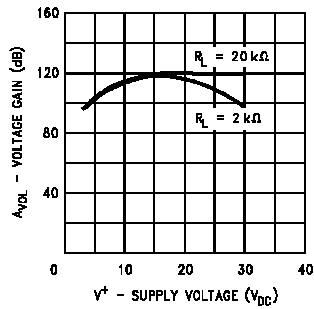
DS009299-35

Supply Current



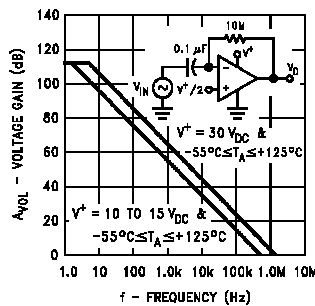
DS009299-36

Voltage Gain



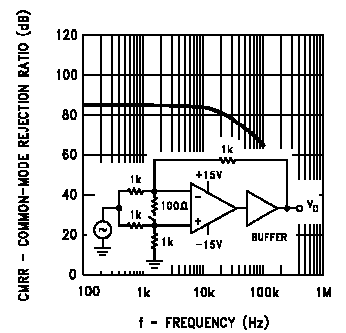
DS009299-37

Open Loop Frequency Response



DS009299-38

Common Mode Rejection Ratio

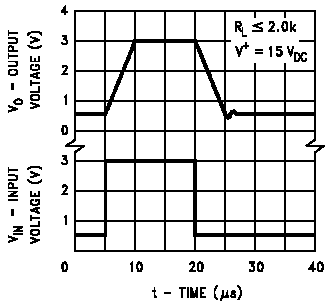


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Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

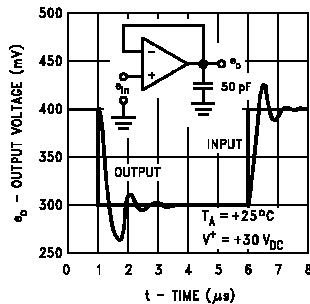
Typical Performance Characteristics (Continued)

Voltage Follower Pulse Response



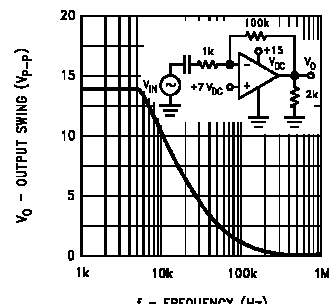
DS009299-40

Voltage Follower Pulse Response (Small Signal)



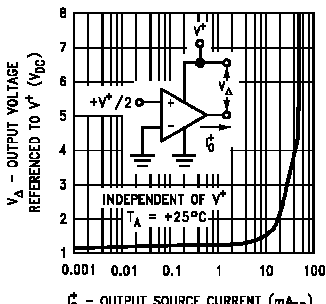
DS009299-41

Large Signal Frequency Response



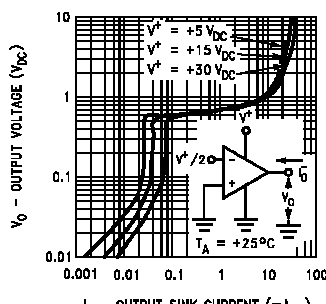
DS009299-42

Output Characteristics Current Sourcing



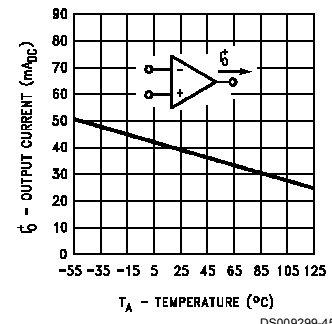
DS009299-43

Output Characteristics Current Sinking



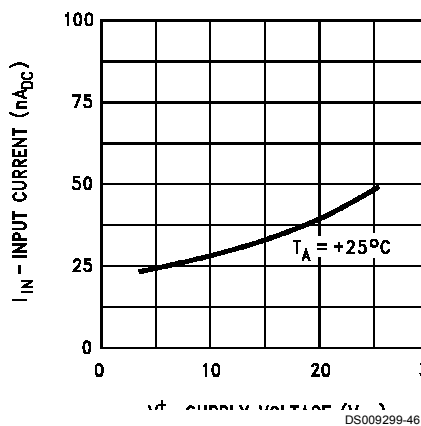
DS009299-44

Current Limiting



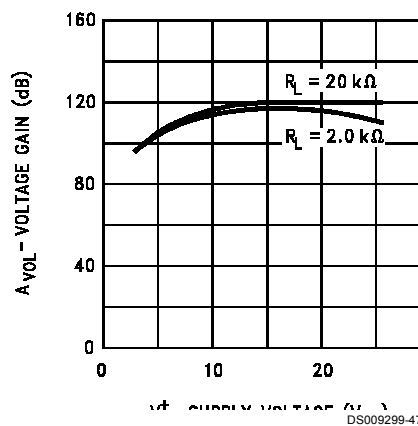
DS009299-45

Input Current (LM2902 only)



DS009299-46

Voltage Gain (LM2902 only)



DS009299-47

Application Hints

The LM124 series are op amps which operate with only a single power supply voltage, have true-differential inputs, and remain in the linear mode with an input common-mode voltage of 0 V_{DC}. These amplifiers operate over a wide range of power supply voltage with little change in performance characteristics. At 25°C amplifier operation is possible down to a minimum supply voltage of 2.3 V_{DC}.

The pinouts of the package have been designed to simplify PC board layouts. Inverting inputs are adjacent to outputs for all of the amplifiers and the outputs have also been placed at the corners of the package (pins 1, 7, 8, and 14).

Precautions should be taken to insure that the power supply for the integrated circuit never becomes reversed in polarity or that the unit is not inadvertently installed backwards in a

Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

Application Hints (Continued)

test socket as an unlimited current surge through the resulting forward diode within the IC could cause fusing of the internal conductors and result in a destroyed unit.

Large differential input voltages can be easily accommodated and, as input differential voltage protection diodes are not needed, no large input currents result from large differential input voltages. The differential input voltage may be larger than V^+ without damaging the device. Protection should be provided to prevent the input voltages from going negative more than $-0.3 V_{DC}$ (at 25°C). An input clamp diode with a resistor to the IC input terminal can be used.

To reduce the power supply drain, the amplifiers have a class A output stage for small signal levels which converts to class B in a large signal mode. This allows the amplifiers to both source and sink large output currents. Therefore both NPN and PNP external current boost transistors can be used to extend the power capability of the basic amplifiers. The output voltage needs to raise approximately 1 diode drop above ground to bias the on-chip vertical PNP transistor for output current sinking applications.

For ac applications, where the load is capacitively coupled to the output of the amplifier, a resistor should be used, from the output of the amplifier to ground to increase the class A bias current and prevent crossover distortion.

Where the load is directly coupled, as in dc applications, there is no crossover distortion.

Capacitive loads which are applied directly to the output of the amplifier reduce the loop stability margin. Values of 50 pF can be accommodated using the worst-case

non-inverting unity gain connection. Large closed loop gains or resistive isolation should be used if larger load capacitance must be driven by the amplifier.

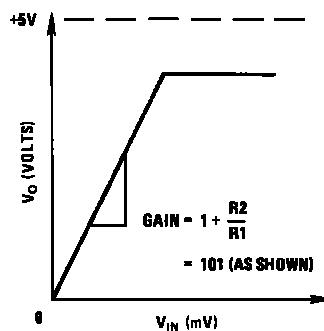
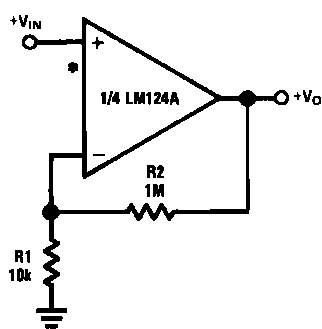
The bias network of the LM124 establishes a drain current which is independent of the magnitude of the power supply voltage over the range of from $3 V_{DC}$ to $30 V_{DC}$.

Output short circuits either to ground or to the positive power supply should be of short time duration. Units can be destroyed, not as a result of the short circuit current causing metal fusing, but rather due to the large increase in IC chip dissipation which will cause eventual failure due to excessive junction temperatures. Putting direct short-circuits on more than one amplifier at a time will increase the total IC power dissipation to destructive levels, if not properly protected with external dissipation limiting resistors in series with the output leads of the amplifiers. The larger value of output source current which is available at 25°C provides a larger output current capability at elevated temperatures (see typical performance characteristics) than a standard IC op amp.

The circuits presented in the section on typical applications emphasize operation on only a single power supply voltage. If complementary power supplies are available, all of the standard op amp circuits can be used. In general, introducing a pseudo-ground (a bias voltage reference of $V^+/2$) will allow operation above and below this value in single power supply systems. Many application circuits are shown which take advantage of the wide input common-mode voltage range which includes ground. In most cases, input biasing is not required and input voltages which range to ground can easily be accommodated.

Typical Single-Supply Applications ($V^+ = 5.0 V_{DC}$)

Non-Inverting DC Gain (0V Input = 0V Output)



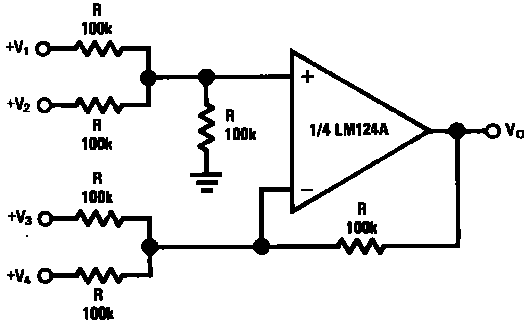
DS009299-5

*R not needed due to temperature independent I_{IN}

Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

Typical Single-Supply Applications ($V^+ = 5.0 V_{DC}$) (Continued)

DC Summing Amplifier
 $(V_{IN's} \geq 0 V_{DC} \text{ and } V_O \geq V_{DC})$

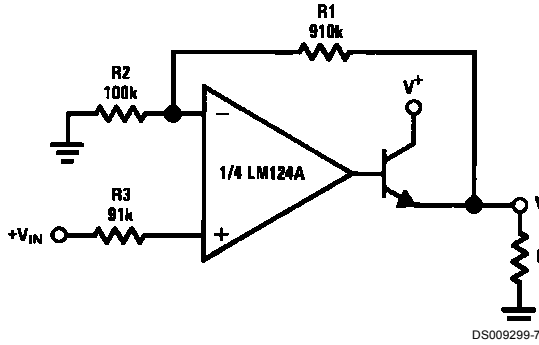


DS009299-6

$V_O = 0 V_{DC}$ for $V_{IN} = 0 V_{DC}$
 $A_V = 10$

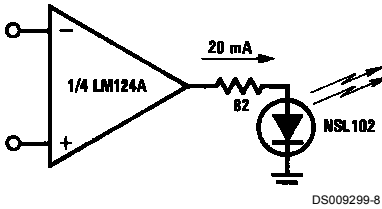
Where: $V_O = V_1 + V_2 - V_3 - V_4$
 $(V_1 + V_2) \geq (V_3 + V_4)$ to keep $V_O > 0 V_{DC}$

Power Amplifier



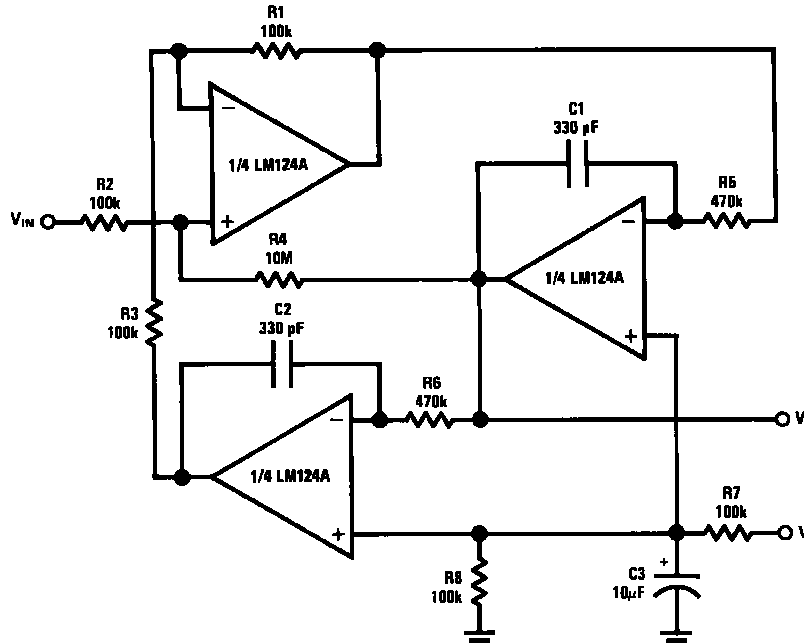
DS009299-7

LED Driver



DS009299-8

"BI-QUAD" RC Active Bandpass Filter



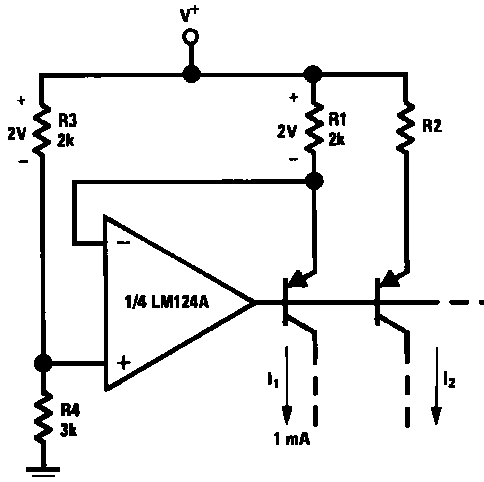
DS009299-9

$f_0 = 1 \text{ kHz}$
 $Q = 50$
 $A_V = 100 \text{ (40 dB)}$

Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

Typical Single-Supply Applications ($V^+ = 5.0 V_{DC}$) (Continued)

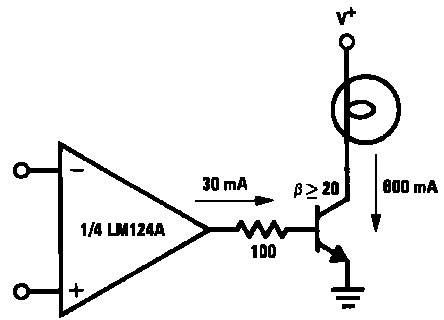
Fixed Current Sources



DS009299-10

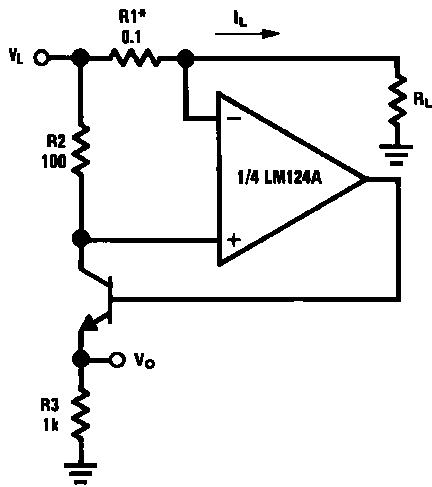
$$I_2 = \left(\frac{R_1}{R_2}\right) I_1$$

Lamp Driver



DS009299-11

Current Monitor



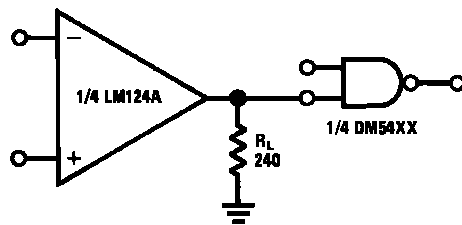
DS009299-12

$$V_o = \frac{1V(I_L)}{1A}$$

$$V_L \leq V^+ - 2V$$

*(Increase R1 for I_L small)

Driving TTL

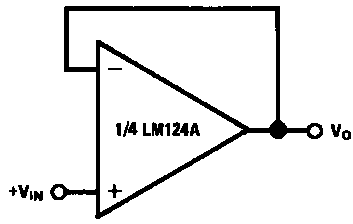


DS009299-13

Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

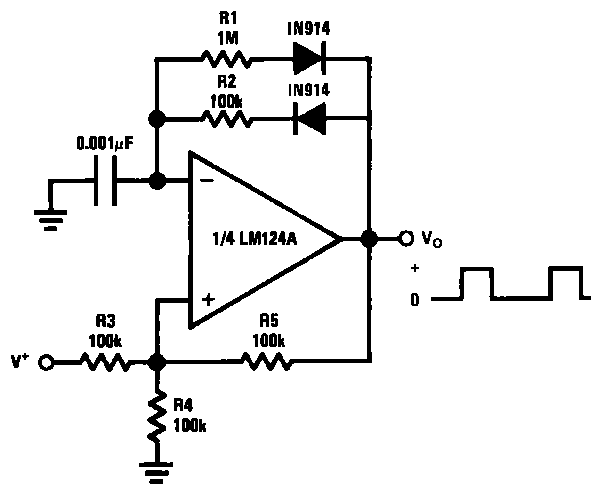
Typical Single-Supply Applications ($V^+ = 5.0 V_{DC}$) (Continued)

Voltage Follower



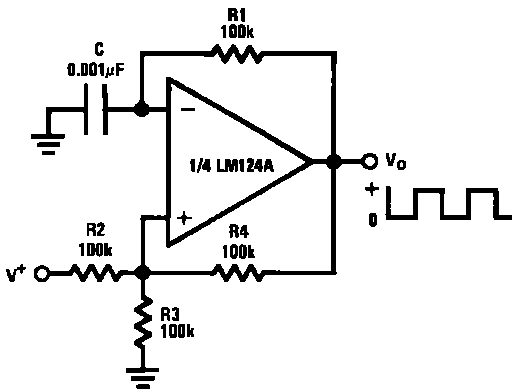
DS009299-14

Pulse Generator



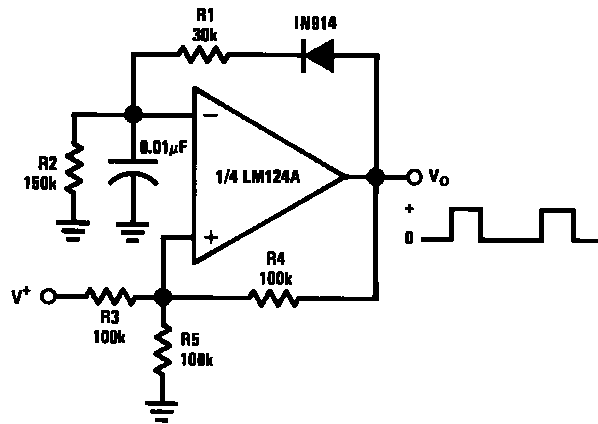
DS009299-15

Squarewave Oscillator



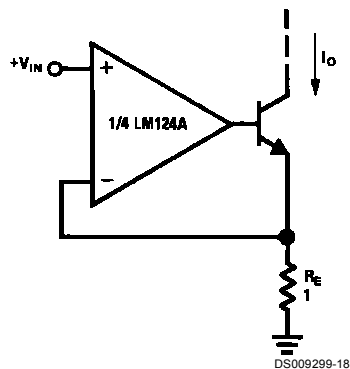
DS009299-16

Pulse Generator



DS009299-17

High Compliance Current Sink



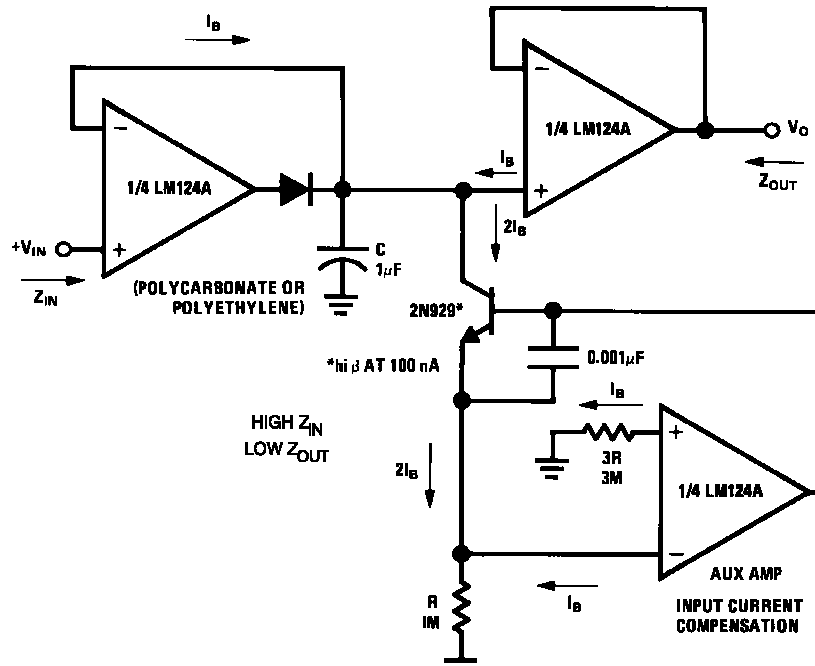
DS009299-18

$I_O = 1 \text{ amp/volt } V_{IN}$
(Increase R_E for I_O small)

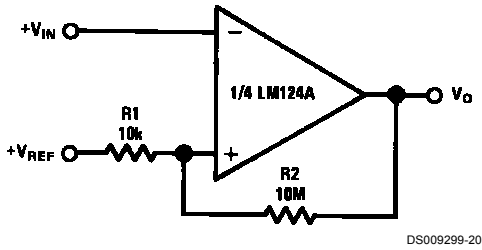
Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

Typical Single-Supply Applications ($V^+ = 5.0 V_{DC}$) (Continued)

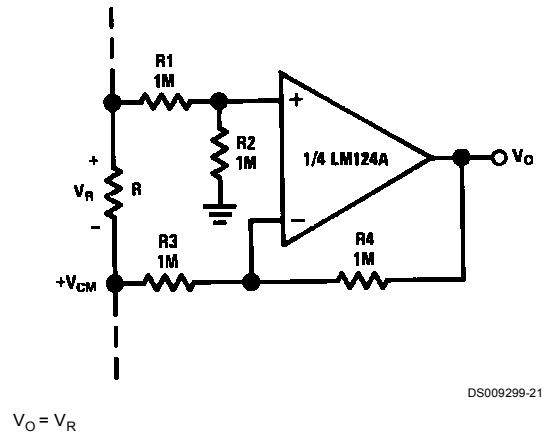
Low Drift Peak Detector



Comparator with Hysteresis



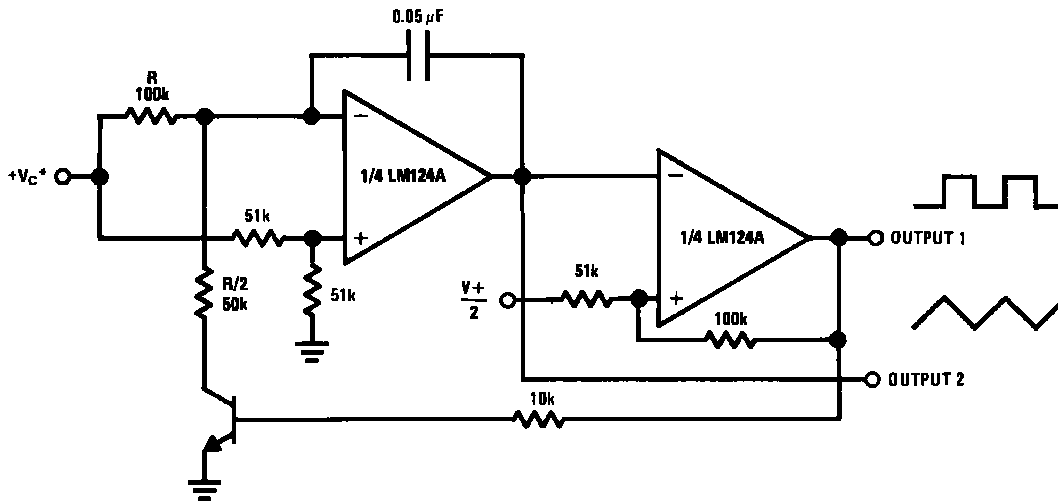
Ground Referencing a Differential Input Signal



Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

Typical Single-Supply Applications $(V^+ = 5.0 V_{DC})$ (Continued)

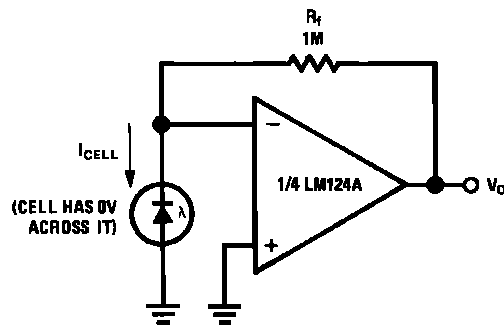
Voltage Controlled Oscillator Circuit



DS009299-22

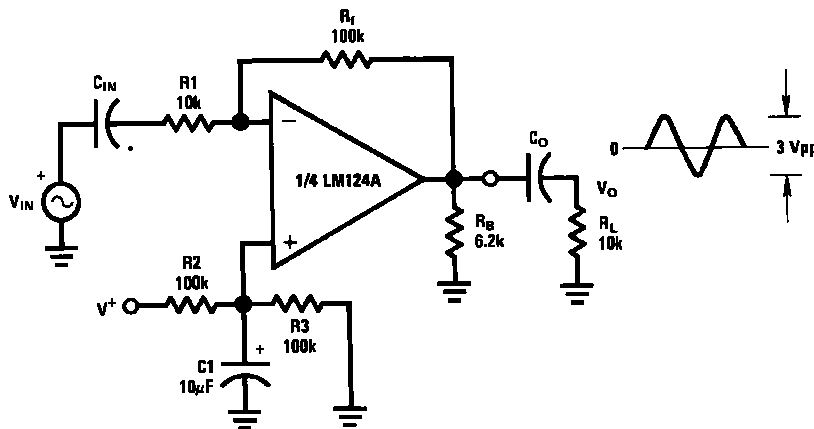
*Wide control voltage range: $0 V_{DC} \leq V_C \leq 2 (V^+ - 1.5 V_{DC})$

Photo Voltaic-Cell Amplifier



DS009299-23

AC Coupled Inverting Amplifier



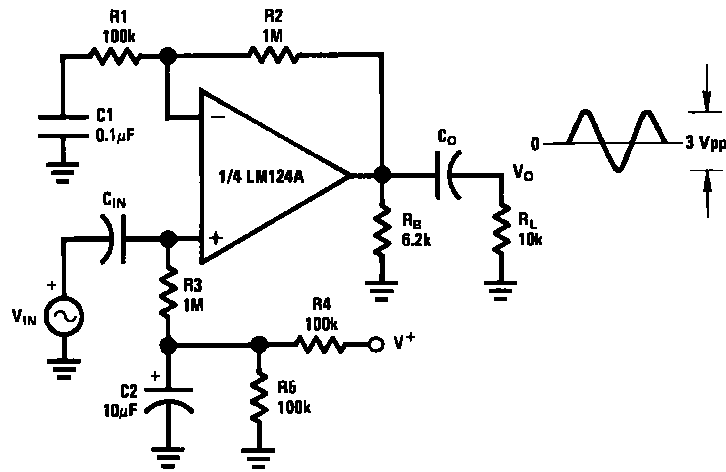
DS009299-24

$$A_V = \frac{R_f}{R_1} \text{ (As shown, } A_V = 10 \text{)}$$

Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

Typical Single-Supply Applications ($V^+ = 5.0 V_{DC}$) (Continued)

AC Coupled Non-Inverting Amplifier

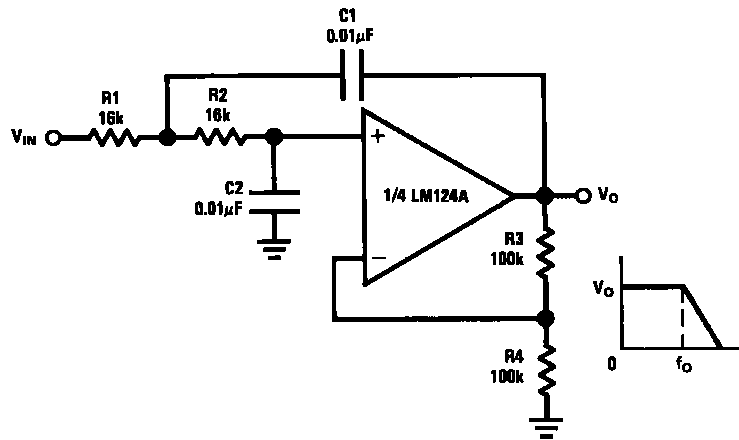


DS009299-25

$$A_V = 1 + \frac{R_2}{R_1}$$

$A_V = 11$ (As shown)

DC Coupled Low-Pass RC Active Filter



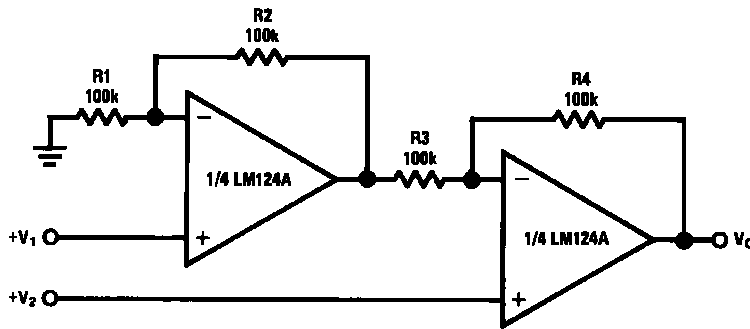
DS009299-26

$f_0 = 1 \text{ kHz}$
 $Q = 1$
 $A_V = 2$

Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

Typical Single-Supply Applications $(V^+ = 5.0 V_{DC})$ (Continued)

High Input Z, DC Differential Amplifier



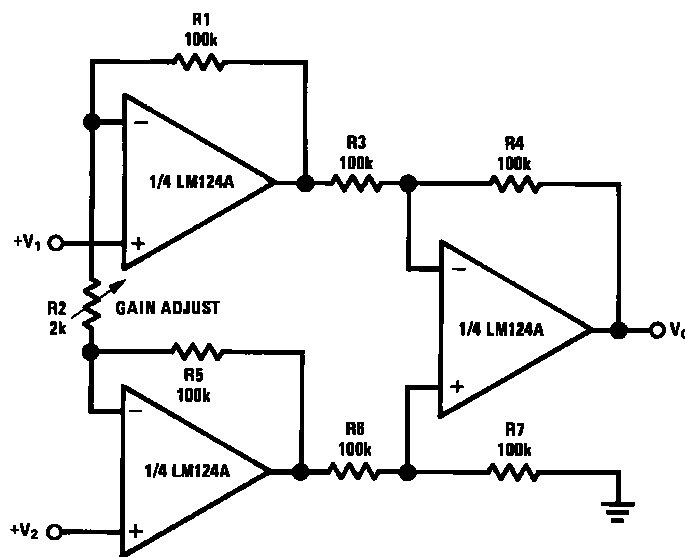
DS009299-27

For $\frac{R1}{R2} = \frac{R4}{R3}$ (CMRR depends on this resistor ratio match)

$$V_O = 1 + \frac{R4}{R3} (V_2 - V_1)$$

As shown: $V_O = 2(V_2 - V_1)$

High Input Z Adjustable-Gain
DC Instrumentation Amplifier



DS009299-28

If $R1 = R5$ & $R3 = R4 = R6 = R7$ (CMRR depends on match)

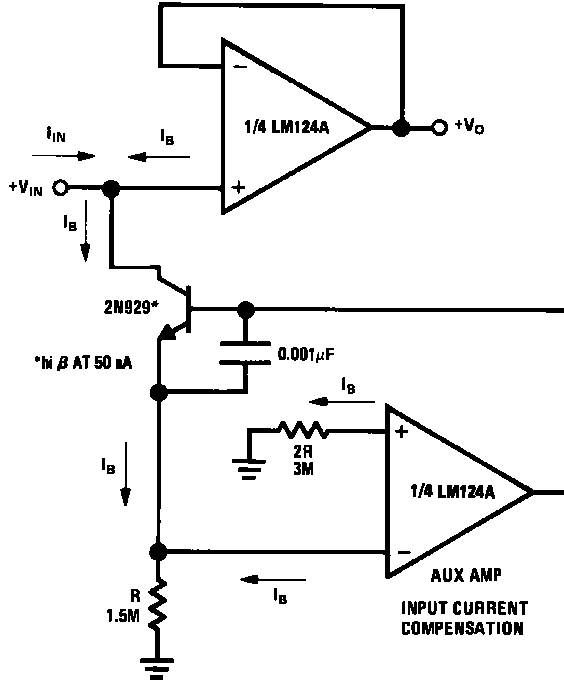
$$V_O = 1 + \frac{2R1}{R2} (V_2 - V_1)$$

As shown $V_O = 101 (V_2 - V_1)$

Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

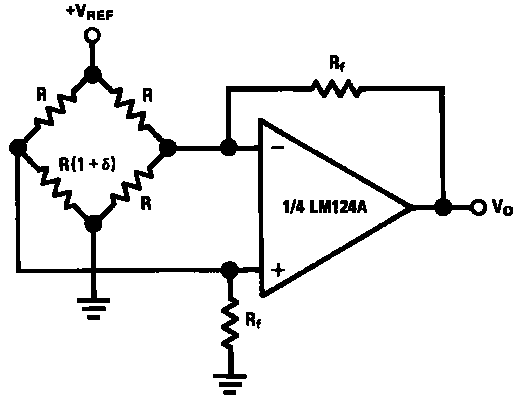
Typical Single-Supply Applications ($V^+ = 5.0 V_{DC}$) (Continued)

Using Symmetrical Amplifiers to Reduce Input Current (General Concept)



DS009299-29

Bridge Current Amplifier

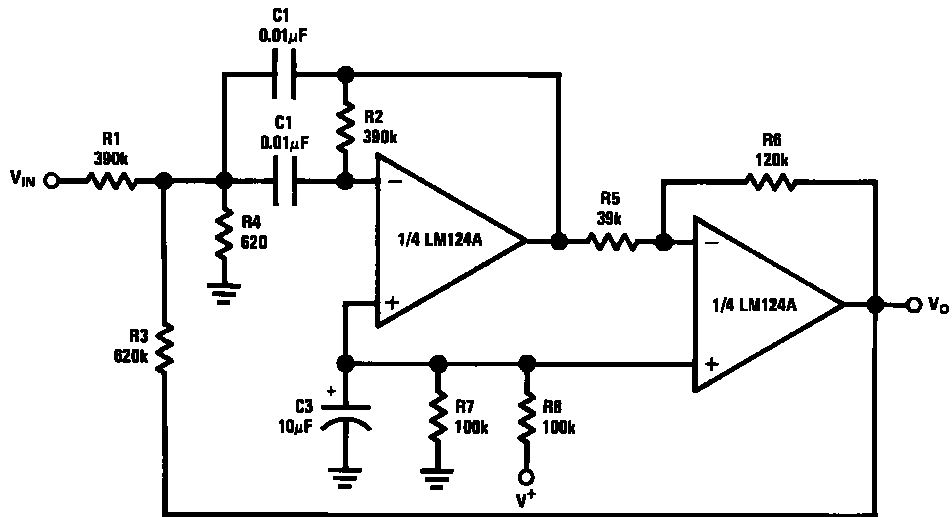


DS009299-30

For $\delta \ll 1$ and $R_f \gg F$

$$V_O \approx V_{REF} \left(\frac{\delta}{2} \right) \frac{R}{F}$$

Bandpass Active Filter

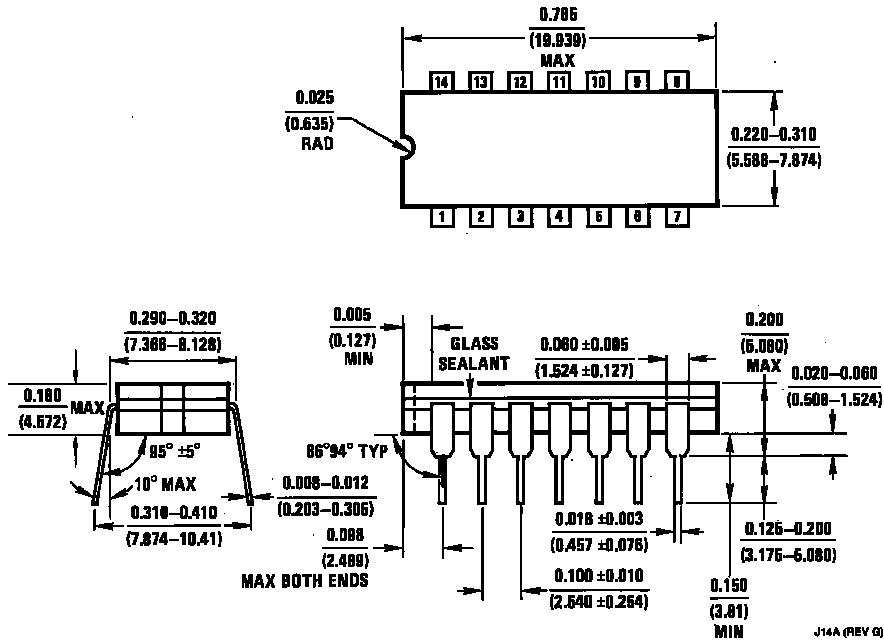


DS009299-31

$f_0 = 1 \text{ kHz}$
 $Q = 25$

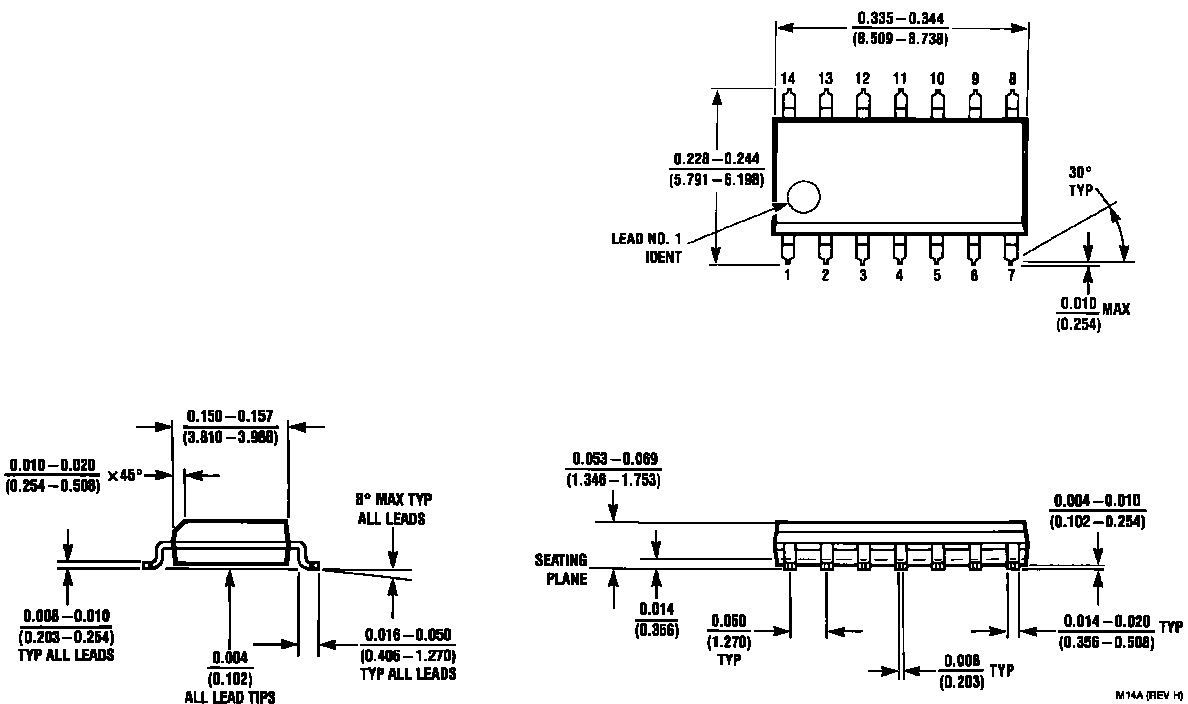
Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

Physical Dimensions inches (millimeters) unless otherwise noted



Ceramic Dual-In-Line Package (J)

Order Number LM124J, LM124AJ, LM124AJ/883, LM124J/883, LM224J, LM224AJ or LM324J
NS Package Number J14A

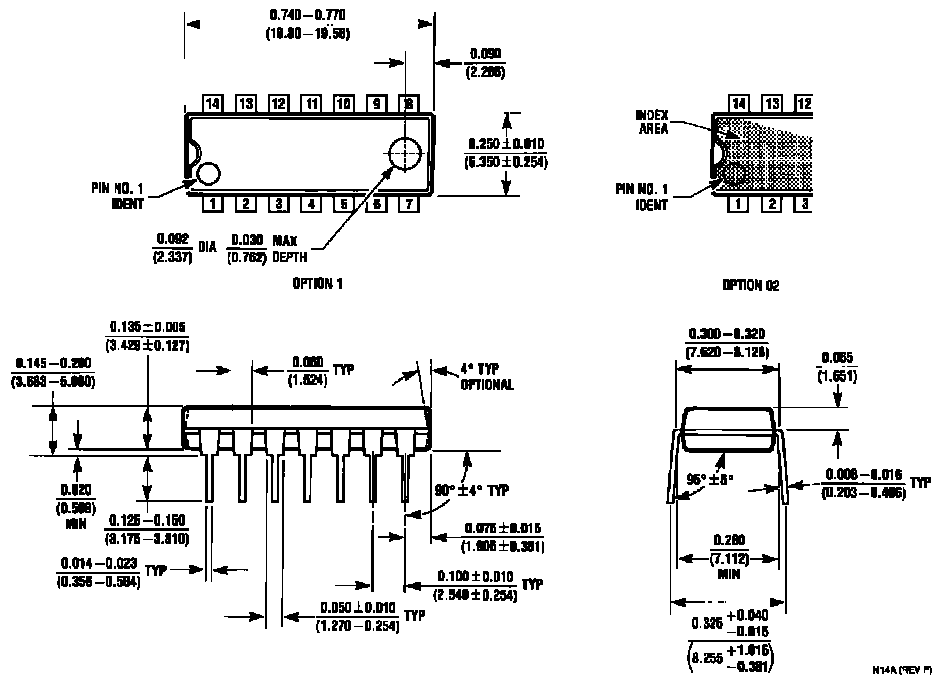


S.O. Package (M)

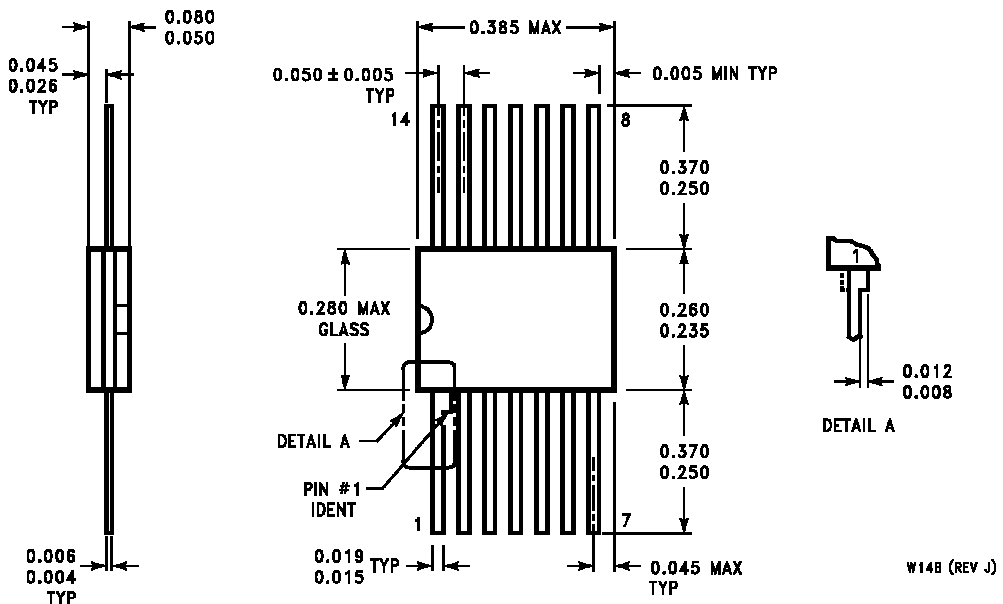
Order Number LM324M, LM324AM or LM2902M
NS Package Number M14A

Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)



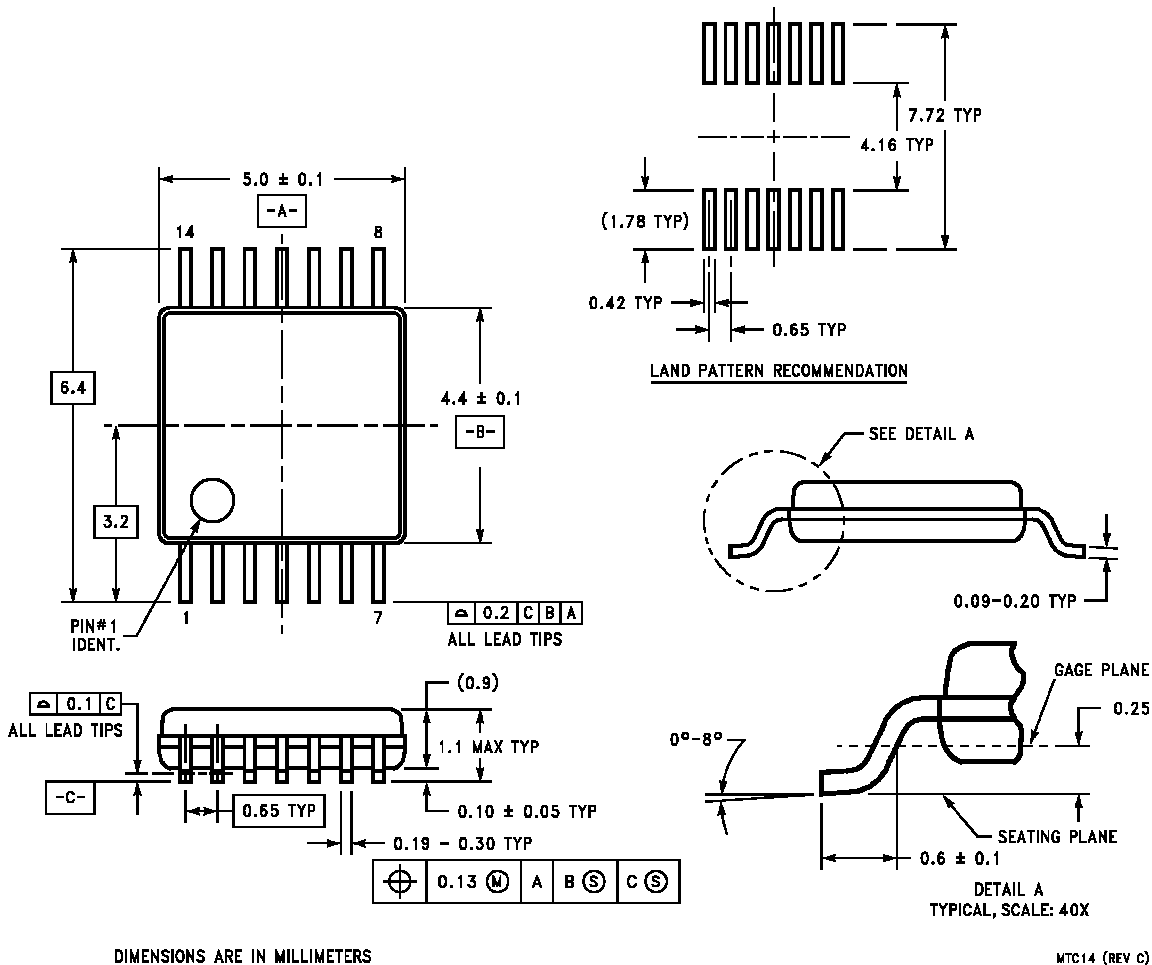
Molded Dual-In-Line Package (N)
 Order Number LM324N, LM324AN or LM2902N
 NS Package Number N14A



Ceramic Flatpak Package
 Order Number LM124AW/883 or LM124W/883
 NS Package Number W14B

Lampiran 5 Data sheet Integrated Circuit (IC) LM 324

Physical Dimensions inches (millimeters) unless otherwise noted (Continued)



LM124/LM224/LM324/LM2902 Low Power Quad Operational Amplifiers

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