TECNOLÓGICO
DE MONTERREY®

Instituto Tecnológico y de Estudios Superiores de Monterrey

Campus Ciudad de México

División de Ingeniería y Arquitectura

Ingeniería Mecatrónica II

Departamento de Ingeniería Eléctrica y Electrónica

Bicicleta Virtual

Autores: Juan Carlos Barradas Elvira [redacted]
Illiana Rocío Alcántara Cabral

Asesor de electrónica: M. en C. Marco Alfredo Castro

Asesor de control: Dr. Ernesto Olguín Díaz

México D.F. a 3 de mayo de 2004.

INDICE

1. Introducción

Las personas que practican ciclismo tienen la necesidad de transportase a diferentes sitios donde puedan encontrar condiciones climatológicas y geográficas aptas para su entrenamiento, ya sea una montaña con diferentes inclinaciones, caminos sinuosos o bien trazados como una carretera, además de las condiciones climáticas que influyen en el recorrido.

A pesar de que existen bicicletas fijas en donde se puede variar la resistencia en el pedaleo, ninguna de ellas simula la totalidad de fuerzas que se presentan en un recorrido real, por eso se decidió hacer este un sistema mecatrónico que emulara las fuerzas presentes en un recorrido.

El proyecto de Bicicleta virtual consiste en el desarrollo de las etapas de electrónica de potencia y la instrumentación para una máquina eléctrica accionada mediante corriente directa, que puede actuar como motor y como generador y que formará parte del sistema físico, junto con una bicicleta comercial de ruta montada sobre unos rodillos que se unen al motor por medio de una banda. Este motor representará el esfuerzo que tendrá que realizar el ciclista de acuerdo con ciertas condiciones y rutas programadas en una computadora.

Este sistema de bicicleta virtual permite simular una trayectoria real, es decir, que se le podrá programar una ruta determinada con pendientes de diversos ángulos de inclinación, considerando efectos físicos, con la finalidad de que las personas que disfruten del ciclismo o deseen practicarlo y no puedan transportarse a un lugar donde puedan hacerlo, lo practiquen.

Cuando un ciclista se encuentra practicando, en un recorrido se le presentan fuerzas que se oponen al desplazamiento estas fuerzas deben ser vencidas por el ciclista y son:

- Resistencia aerodinámica
- Resistencia por pendiente
- La inercia
- Fuerza de fricción
  - Por contacto de las llantas y el pavimento
  - Por rodamientos internos de la bicicleta

1.1 Objetivo

El objetivo de este proyecto de Ingeniería Mecatrónica es realizar la instrumentación y el desarrollo de la electrónica de potencia del sistema cuando trabaja como motor y como generador. Los objetivos logrados en este proyecto de ingeniería mecatrónica fueron:

1. Etapa de potencia como motor.
2. Instrumentación.
3. Caracterización del motor de corriente directa.
4. Modelo en Matlab de un motor de CD.

1.2 Áreas de Desarrollo

- Electrónica Analógica
- Electrónica Digital
- Electrónica de Potencia
- Ingeniería de Control
- Háptica
- Investigación
- Deportes

1.3 Estado del Arte

El modelado de sistemas mecánicos representa una herramienta para el análisis y desarrollo de aplicaciones prácticas. Algunas de las más comunes son las máquinas de entrenamiento que recrean condiciones reales por medio de la simulación de variables como pueden ser temperatura, tensión y otras.

Las bicicletas estacionarias han sido comúnmente utilizadas para tener los beneficios fisiológicos y físicos que las bicicletas normales proporcionan a un atleta. Así se pueden ver bicicletas en cualquier centro de acondicionamiento físico, e incluso en casas de particulares. Estas bicicletas sirven para tonificar los músculos e incrementar la capacidad aeróbica, mas no ayudan a mejorar la capacidad del ciclista de procesar la velocidad y los cambios en el esfuerzo que tiene que ejercer en su entrenamiento.

Existen otras bicicletas estacionarias que los atletas de alto rendimiento utilizan para entrenar antes de sus competencias, y que presentan características como el control de velocidades y pendientes para incrementar la potencia y las habilidades técnicas del usuario.

Actualmente ya existen en el mercado bicicletas fijas donde se puede variar la resistencia en el pedaleo como el Spintrainer [21] que permite simular la forma más fiel posible la marcha en carretera de una bicicleta. La gestión computarizada del sistema de frenado de la máquina permite controlar continuamente la velocidad de avance, la pendiente y la resistencia del aire pero no simula de simula de manera precisa todas las fuerzas presentes en el sistema real y esto sucede con muchas otras bicicletas que ya existen. Los entrenadores que existen actualmente en el mercado, tiene un sistema magnético de resistencia, también los hay con sistemas de resistencia por fluidos, con aceite, o de motores.

Otra de las áreas de la tecnología relacionadas con nuestro proyecto es la háptica o "haptics" en inglés. La háptica [20] es la ciencia que se encarga de crear sensaciones similares a las que el usuario tendría en una recorrido real, y esto lo logra por medio de una retroalimentación basada en aplicaciones de computadora en conjunto con un "display" visual. En los proyectos, simuladores y aparatos ya existentes la háptica no ha sido aplicada a ellos.

1.4 Infraestructura Necesaria

Se utilizaron las instalaciones del Laboratorio de Robótica y los siguientes instrumentos:

- Fuentes de alimentación
- Osciloscopios
- Sistema bicicleta motor
- Computadora personal con Matlab
- Generadores de funciones
- Componentes electrónicos varios para fuente y tacómetro.
- Amperímetro de Gancho

1.5 Actividades

Las actividades realizadas durante este proyecto de ingeniería fueron:

A) Etapa de Potencia

Fuentes de voltaje de CD.

Modulador Astable y Convertido Buck-Step Down

Simulación e Integración de Circuitos

B) Instrumentación

Elaboración de tacómetros.

Sensor de corriente.

Simulación e integración de circuitos

C) Caracterización de una máquina de CD

Estándar IEEE std. 113-1985

Generadores de CD

2. Desarrollo

2.1 Etapa de Potencia

2.1.1 Electrónica de Potencia

La tarea de la electrónica de potencia es controlar el flujo de energía eléctrica de manera que proporcione voltajes y corrientes que sean útiles para el manejo de cargas. Además que la electrónica de potencia nos ayuda a que no existan pérdidas de potencia muy grandes y que tengamos una eficiencia alta, en la electrónica lineal esto no es posible ya que en esta los dispositivos operan en una región lineal.

La electrónica de potencia tiene 4 grandes campos de aplicación, este proyecto se enfoca en la de control de procesos y automatización industrial. El control de máquinas de corriente directa es mucho más eficiente gracias a las mejoras en los semiconductores de potencia. Al utilizar semiconductores de potencia en las configuraciones básicas de circuitos es posible arrancar, parar, aumentar o disminuir la velocidad, y dar reversa a un motor de CD. Estas funciones se pueden llevar a cabo con un grado muy fino de control con la ventaja adicional de mayor eficiencia y confiabilidad del sistema. Es importante mencionar que para lograr un mejor desempeño de la etapa de potencia de la bicicleta virtual tenemos que usar una configuración como la que se presenta a continuación:

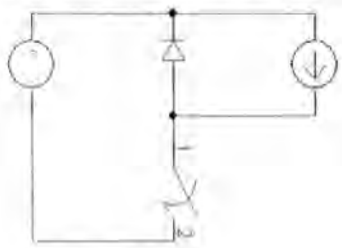


Figura 1.

Este arreglo se hace para asegurar:

1. Que la velocidad de respuesta sea rápida.
2. Que la potencia requerida para accionar el "switch" sea baja.
3. Conducir corrientes altas con ninguna caída de voltaje al momento de accionar el "switch".

2.1.2 Fuentes de voltaje de CD

En este proyecto se utiliza un motor de corriente directa de excitación separada, con una velocidad nominal de 1750 rpm, que ofrece una mejor y más fácil regulación de la velocidad, simplemente variando la tensión a la entrada del motor de la armadura y manteniendo el campo constante. En la figura se muestra el diagrama eléctrico de un motor de CD de excitación separada, que es el tipo de motor que se utilizará este proyecto.

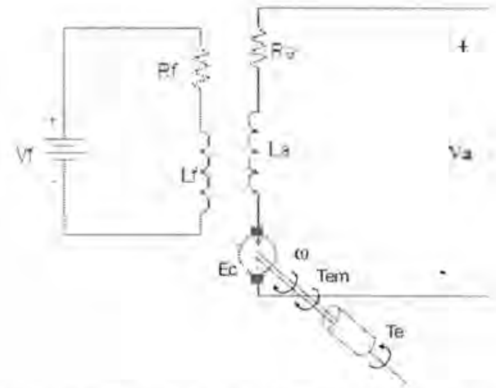


Figura 2. Diagrama eléctrico de un motor de CD de excitación separada [1]

Entre los inconvenientes que presenta este tipo de motores podemos nombrar que es más caro, tiene un mayor tamaño que el del motor de alterna a una misma potencia, precisa de un mayor mantenimiento.

En comparación un motor de alterna ofrece ventajas como robustez y menor mantenimiento, menor tamaño a igual potencia. Sin embargo presenta una serie de problemas tales como: difícil arranque (puede incluso necesitar algún dispositivo para su arranque) difícil regulación de la velocidad, ya que para controlar el par de la máquina correctamente debemos controlar el flujo, el torque, la frecuencia, cosa que complica en gran medida la regulación del motor.

Se opto por el uso del motor de corriente directa debido a que ya se contaba con este motor en el laboratorio, y al mismo tiempo por la facilidad en el control de velocidad y evitar los posibles problemas que podemos encontrarnos en el arranque en un motor de alterna.

Ahora trataremos las diferentes posibilidades para la alimentación de dicho motor. Dadas las necesidades de nuestro sistema, se trato de hacer funcionar dicho máquina eléctrica tanto como generador como motor, pero cabe hacer la aclaración que solo operará en un solo sentido en función del tramo de la etapa que estemos simulando

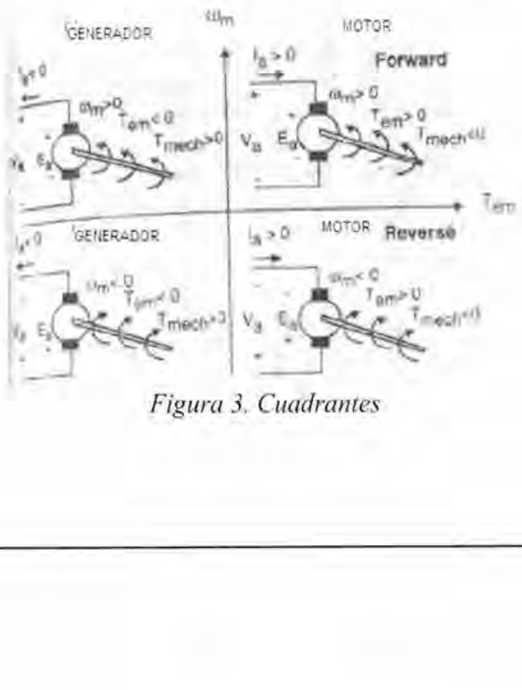


Figura 3. Cuadrantes

Por ello el accionamiento del motor que se usa debe permitirnos trabajar en los dos cuadrantes deseados, cuadrantes uno y dos. Además cabe tener en cuenta que la tensión de que se dispone, es la tensión típica de cualquier hogar. Las posibles soluciones:

- Rectificadores no controlados,
- Rectificadores semicontrolados
- Rectificadores controlados

Los tres anteriores podemos encontrarlos tanto de media onda como de onda completa. La elección se basa en el costo del sistema y la facilidad de control que nos ofrezca cada una, el rectificador controlado exige el control de cuatro variables y puede ser más cara, mientras que un rectificador no controlado exige el control de menos variables y simplifica el control del sistema, permite una frecuencia de conmutación mucho más elevada y puede resultar más barato.

Por lo tanto la alimentación del motor se hará acoplando un generador de pulsos astable a un convertidor Buck-Step Down y la fuente de alimentación diseñada a valores nominales de voltaje en el campo y la armadura.

Datos de placa del Motor

CAT NO. CD 5319			
SPEC 359442Z105			
HP	1	ENCL	TEFC
RPM	1750	SER#	W9-94
FRAME	56C	TYPE	SH3535D
ARM VOLTS	90	AMPS	10
FIELD VOLTS	100/50	AMPS	0.6/1.2
INSUL	F	AMB	40 C
DUTY	CONT	SUPPLY	F.F.1.30
BRG/DE 6205			
BRUSH BP5000P07			

Tabla 1. Datos de Placa del Motor

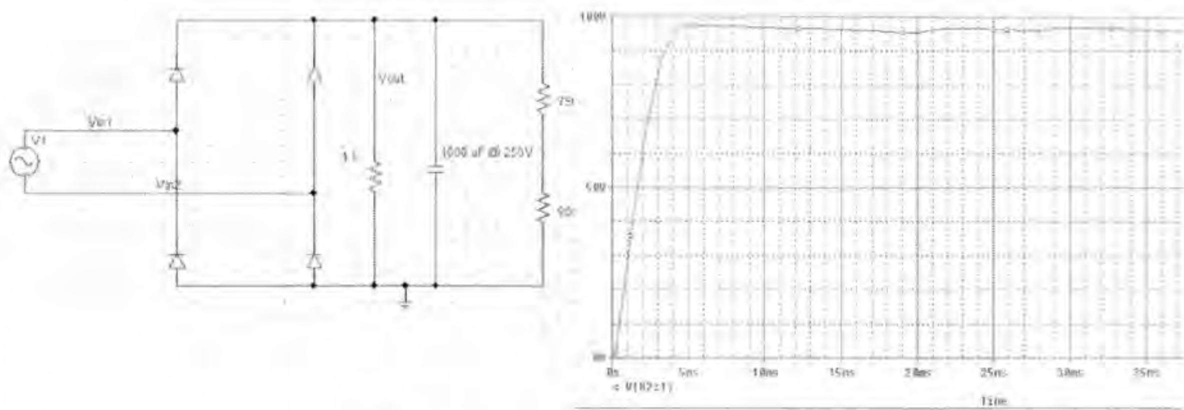


Figura 4. Circuito fuente de voltaje para la armadura

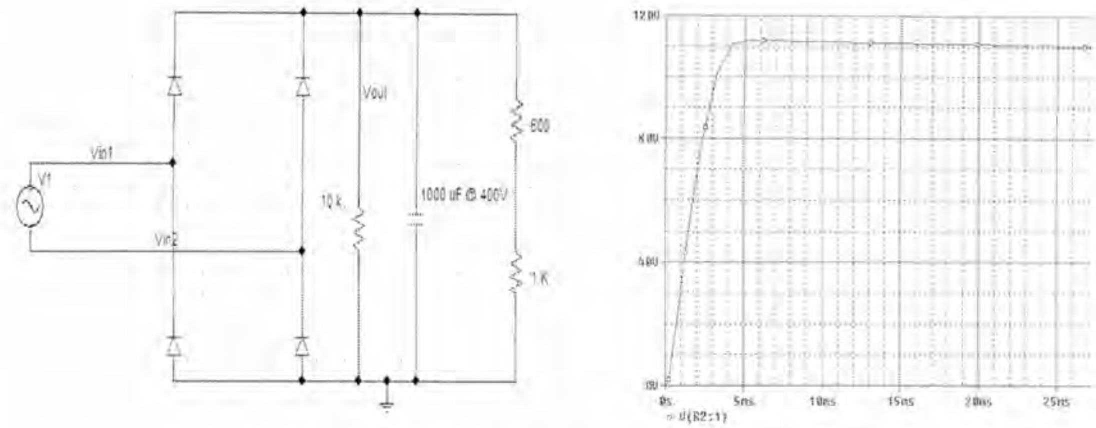


Figura 5. Circuito fuente de voltaje para el campo.

2.1.3 Convertidor Cd-Cd Reductor (Buck Step-Down Converter)

Este convertidor es el más común. El de la forma básica de muchos circuitos de potencia como los inversores. Se utiliza en potencias del rango de decenas de watts (para pequeñas fuentes de alimentación). El rango de operación del buck-converter es de 1kHz en operaciones de alta potencia y de hasta 500kHz.

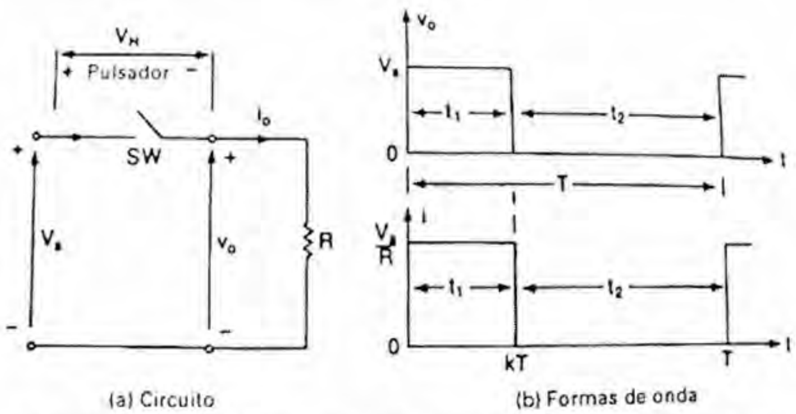


Figura 6. Circuito y Funcionamiento Convertidor Cd-Cd Reductor [15]

Cuando se cierra el interruptor SW durante t1, el voltaje de entrada Vs aparece a través de la carga.
Cuando el interruptor SW se abre durante t2, el voltaje a través de la carga es cero.
El interruptor pulsador en la práctica puede ser:

- BJT de potencia
- MOSFET de potencia
- GTO
- SCR

En el siguiente análisis se considera que el interruptor cualquiera que fuese es ideal.
El voltaje promedio de salida del circuito

$$Va = \frac{1}{T}\int_0^{t_1} v_o dt = \frac{t_1}{T}Vs = f \cdot t_1 Vs = kVs \qquad (2.1.3.0)$$

La corriente de la carga es

$$Ia = \frac{Va}{R} = \frac{kVs}{R} \qquad (2.1.3.1)$$

Donde:

T = es el periodo de pulsación

k = es el ciclo de trabajo $= \frac{t_1}{T}$

f = es la frecuencia del pulso

El voltaje rms de salida se determina a partir de:

$$Vo = \left(\frac{1}{T}\int_0^{kT} v_o^2 dt\right)^{1/2} = \sqrt{k}Vs \qquad (2.1.3.2)$$

Suponiendo que el convertidor no tiene pérdidas, la potencia de entrada es la misma que la potencia de salida y esta dada por

$$Pi = \frac{1}{T}\int_0^{kT} v_o i dt = \frac{i}{T}\int_0^{kT} \frac{v_o^2}{R} dt = k\frac{V_s^2}{R} \qquad (2.1.3.3)$$

La resistencia vista por la fuente es:

$$Ri = \frac{Vs}{I_a} = \frac{Vs}{kVs/R} = \frac{R}{k} \qquad (2.1.3.4)$$

El voltaje de salida Vo puede variar de 0 hasta Vs, haciendo variar el ciclo de trabajo del transistor (k) o la frecuencia de operación. Es obvio que k variará desde 0 hasta 1.

1. Cuando el convertidor trabaja a frecuencia constante y lo que se varía es el ancho de pulso (kT), es decir se varía el t1, el convertidor estará trabajando como control de modulación por ancho de pulso (PWM).

2. Cuando el ciclo de trabajo es constante y lo que se varía es la frecuencia, se conoce como modulación por frecuencia. Este tipo de control generara armónicas a frecuencias no predecibles y el diseño del filtro resultara muy complicado.

A continuación se muestra el circuito del convertidor y la simulación resultante de este.

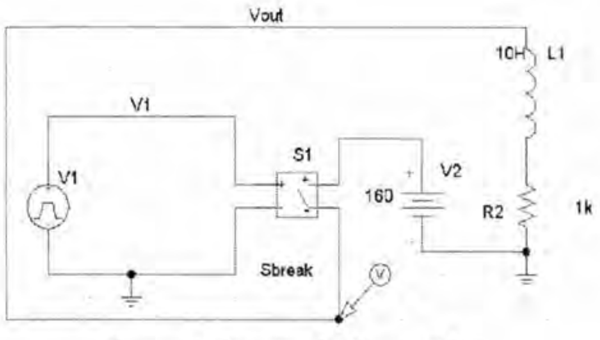
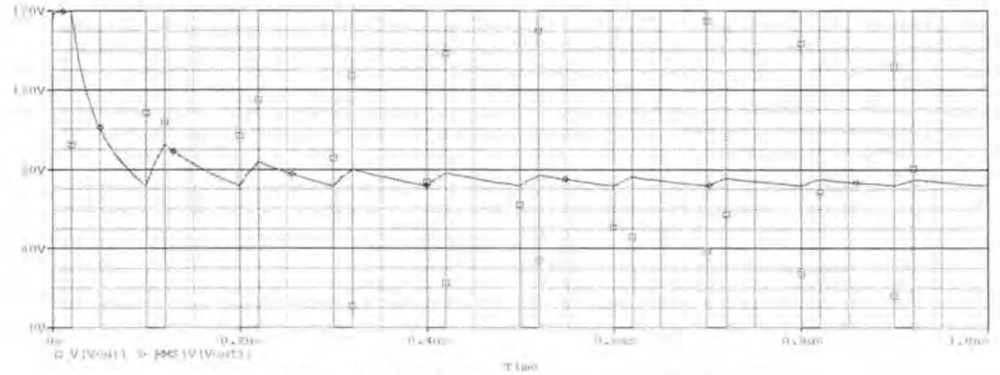


Figura 7. Circuito del Convertidor

Donde Sbreak es un transistor, que vamos a usar en estado de corte y saturación. Y la resistencia de 1k es donde se sustituirá por la impedancia del motor.

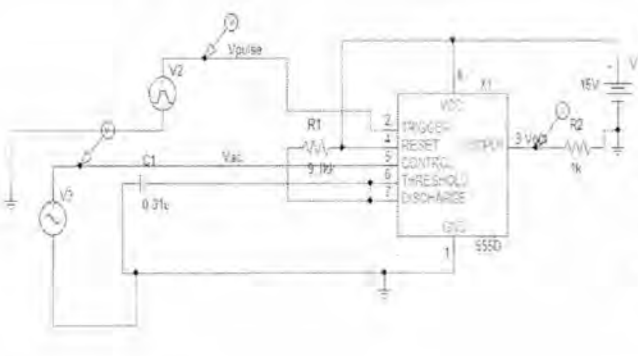


Gráfica 1. Simulación Pspice Valor promedio del voltaje.

La gráfica mostrada anteriormente es el resultado de la simulación del circuito del convertidor en ella se demuestra que dependiendo del pulso que haya en el transistor el voltaje variara de cero a 160, estos parámetros se mostraran cambiados posteriormente, la fuente V1 por el modulador astable y la fuente por una de 100 o 90 Volts.

2.1.4 Modulador por Ancho de Pulso

En el diseño preliminar se optó por usar un PWM para dar los pulsos a la entrada del convertidor, para que este trabaje a frecuencia constante. Y así se variaría el voltaje desde cero hasta 100 o 90 Volts según sea el caso. El circuito que se muestra a continuación es el Modulador por Ancho de Pulso que se uso en el diseño preliminar para las fuentes:



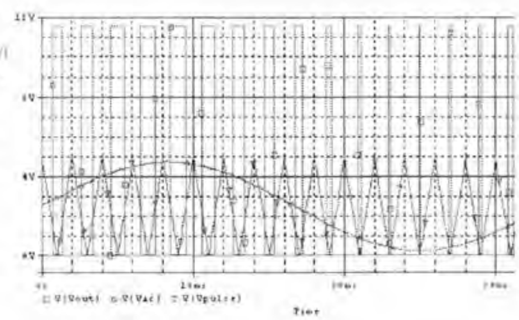


Figura 8. Circuito Modulador por Ancho de Pulso

Este circuito PWM utiliza 1 señal triangular y una senoidal en caso de cada fuente por lo que sería necesario implementar 4 generadores de funciones, esto no solo representa un costo mayor, si no que además el control de la frecuencia de la frecuencia y amplitud de las señales necesarias para obtener un pulsos en milisegundos es mucho mas difícil de conseguir de de variar. Esto nos llevo a cambiar el PWM por un modulador astable usando un LM555.

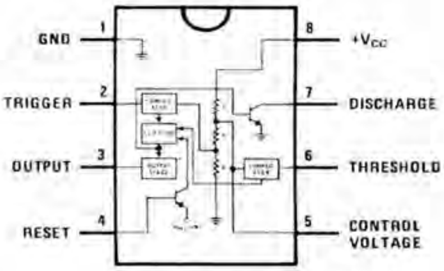


Figura 9. LM 555

2.1.5 Modulador *Astable*

Con esta configuración no son necesarias las señales triangular y cuadrada, pues por la forma de conexión este circuito se dispara y resetea por sí solo, esta configuración es la siguiente:

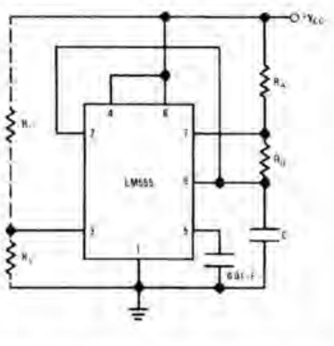


Figura 10. LM 555 Configuración Astable

Para que el ciclo de trabajo varíe es necesario variar las resistencias Rl que se muestran en el diagrama, para conocer el valor de las resistencias se tiene que conocer los tiempo de carga y descarga y por lo tanto el período.

El tiempo de carga (salida alta) esta dado por:

$$t_1 = 0.693(R_A + R_B)C \quad (2.1.5.0)$$

El tiempo de descarga (salida baja) esta dado por:

$$t_2 = 0.693(R_B)C \qquad (2.1.5.1)$$

El período total esta dado por:

$$T = t_1 + t_2 = 0.693(R_A + 2R_B)C \qquad (2.1.5.2)$$

En este caso t_1 es igual a 90ms y t_2 es igual a .10ms por lo tanto T es igual 1ms esto nos da a la salida los pulsos invertidos por lo que antes de esta señalan haga el "switcheo" que permitirá que el voltaje varíe de 0 a 90 Volts, se necesito un negador con el que se obtiene los pulsos deseados que son los que se muestran en la gráfica.

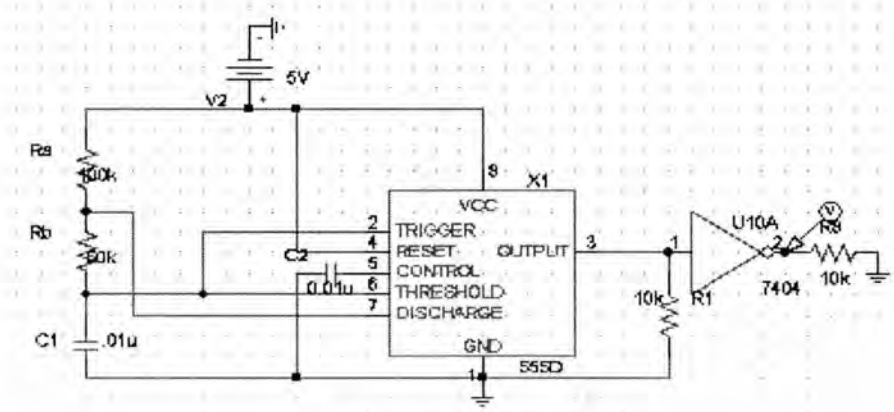
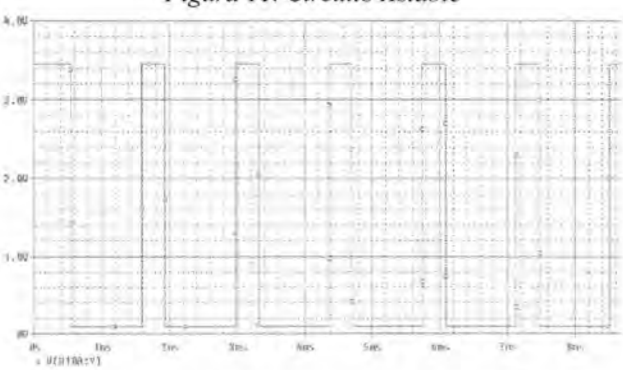


Figura 11. Circuito Astable



Grafica 2. Simulación Pspice Modulador Astable

Una vez simulados los circuitos por separado se procedió a unirlos y quedaron de la siguiente manera:

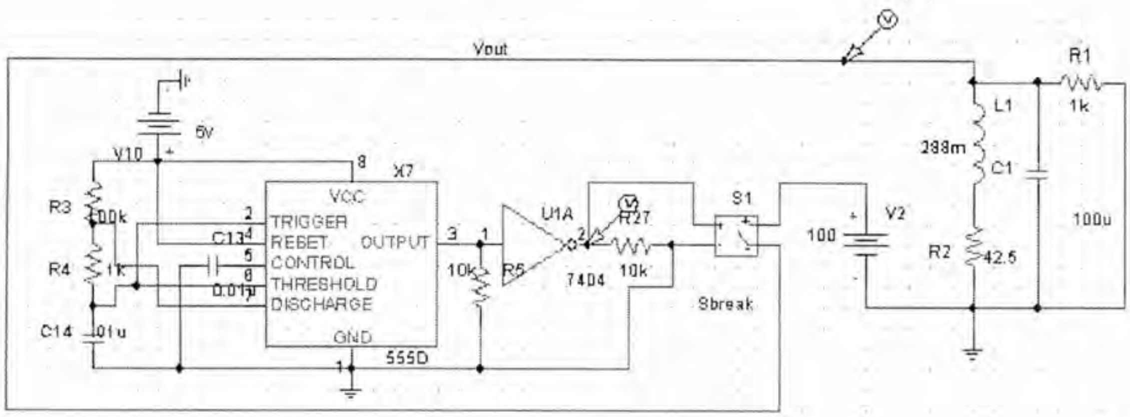
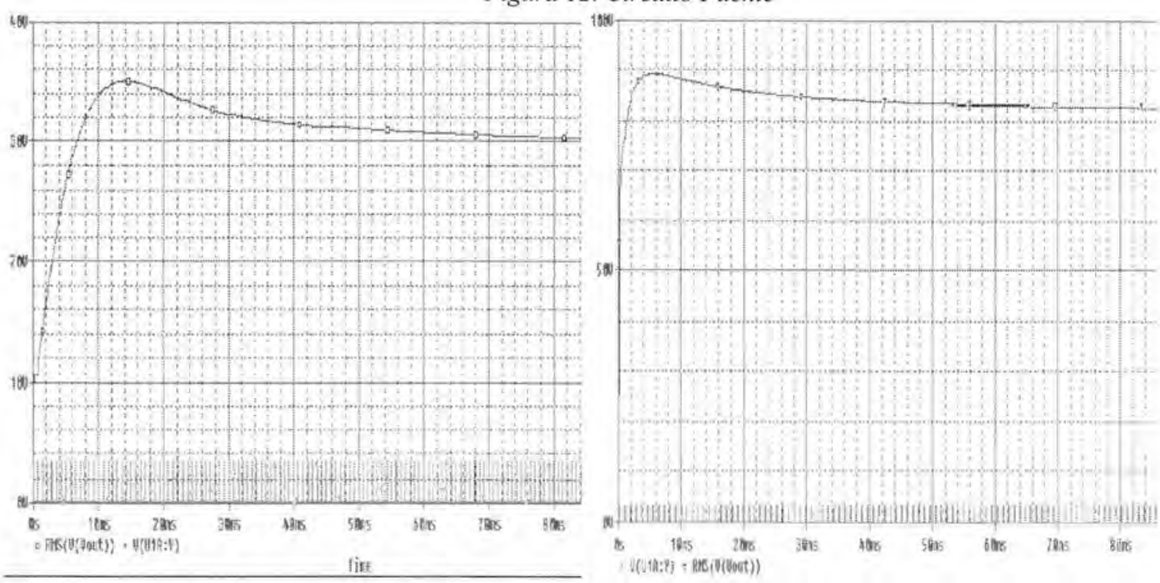


Figura 12. Circuito Fuente



Gráfica 3,4 .Simulación Pspice variación del voltaje de la Fuente

2.2 Instrumentación

2.2.1 Tacómetro

Los tacómetros son dispositivos que sirven para medir la velocidad de rotación, se dividen en tres grandes tipos de acuerdo a su salida, que puede ser:

1. Un valor de voltaje: Tacogeneradores.
2. Una indicación visual: Tacómetros "Fly Ball"
3. Una frecuencia: tacómetros de pulsos ópticos, capacitancia variable, efecto hall y estroboscopios.

Los primeros tacómetros que se usarían, serían unos tacómetros ópticos comprados; debido al alto costo de esto decidimos hacer nuestros propios tacómetros.

Para este proyecto de bicicleta virtual se construyeron dos tacómetros mediante el método de luz incidente. Estos tacómetros generan un tren de pulsos cuya frecuencia es proporcional a la velocidad de rotación a ser medida. Esta frecuencia de pulsos puede ser medida de manera digital o analógica.

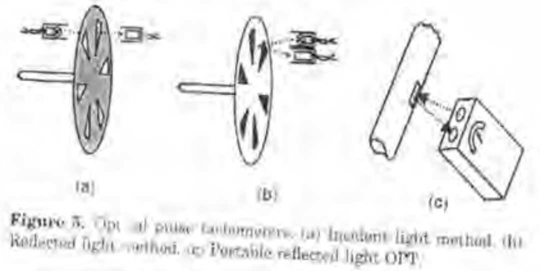


Figura 13. Tacómetro de pulso ópticos [6]

Los pulsos pueden ser generados de dos formas alternativas: por el método de luz incidente o por el método de la luz reflejada. La frecuencia de salida de los tacómetros ópticos es igual a:

$$f = \frac{nN}{60} \qquad (2.2.1.0)$$

Donde:

n = cantidad de huecos en el disco del tacómetro o cantidad de marcas que reflejan.
N = velocidad en rpm.

Para convertir la frecuencia de salida del tacómetro debemos de hacer una conversión voltaje-frecuencia. Esta conversión está basada en el hecho que el voltaje promedio del tren de pulsos de amplitud constante U, duración constante T0 y un período T es:

$$V = \frac{UT_0}{T} \qquad (2.2.1.1)$$

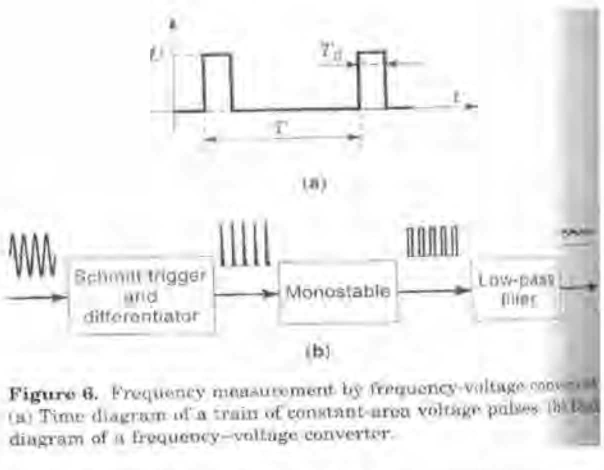


Figura 14. Tren de pulsos (convertidor frecuencia-voltaje) [6]

Algunos de los problemas presentados con el tacómetro, son que éste no tiene un "reset", el reset es necesario para que al iniciar otra prueba el tacómetro tenga valor de cero y no se quede con el valor anterior. Para poder realizar las mediciones con este tacómetro es necesario producir un tren de pulsos, para poder generar este tren de pulsos se adhirió a la polea acoplada al motor un disco dentado de 0.27 m de diámetro y cada diente se encuentra separado una distancia de cinco grados, los cuales fueron medidos con un transportador. Hasta este momento el "reset" al tacómetro se le da moviendo la rueda dentada, un problema es que el hacer las pruebas con mucha luz impide que el tacómetro funcione adecuadamente debido a que es un tacómetro óptico.

Otro detalle interesante del tacómetro es que para que pueda ser accionado y funcione de manera correcta es necesario alimentarle una señal cuadrada de frecuencia 103 mHz y una amplitud en el orden de los 300 a 500 mV. Esta señal mencionada debe ser alimentada en la primera pata del LM2907.

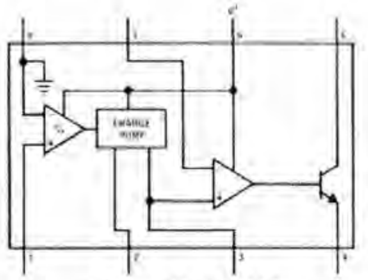


Figura 15. LM 2907

La señal cuadrada se alimenta a la pata uno que es por donde entra en tren de pulsos enviado por el acoplador óptico; por lo que realmente entran dos señales a la primera pata del convertidor frecuencia-voltaje, entra la señal enviada por el acoplador óptico y la señal enviada por un generador de señales de amplitud y frecuencia mencionadas con anteriormente.

A continuación se muestra el diagrama del circuito de tacómetro construido, en el muestra se muestra el diodo emisor de luz infrarrojas la señal que este entrega en negada y de ahí pasa el convertidor frecuencia voltaje, la salida de este la obtenemos en a pata 3.

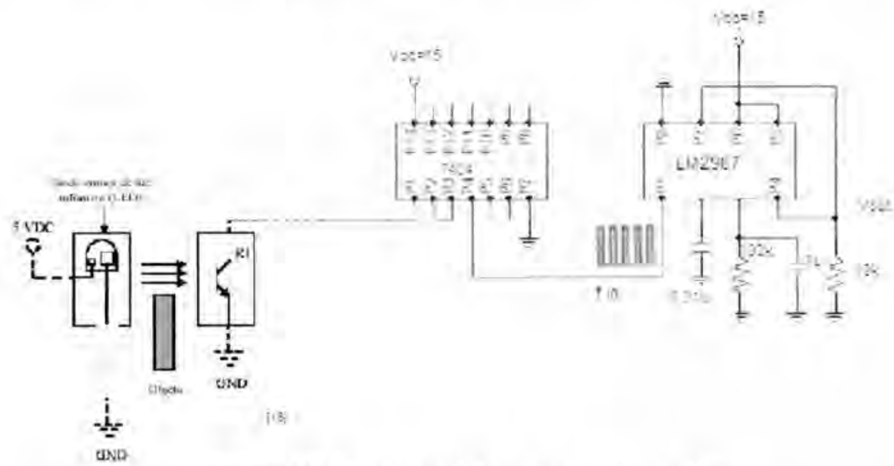
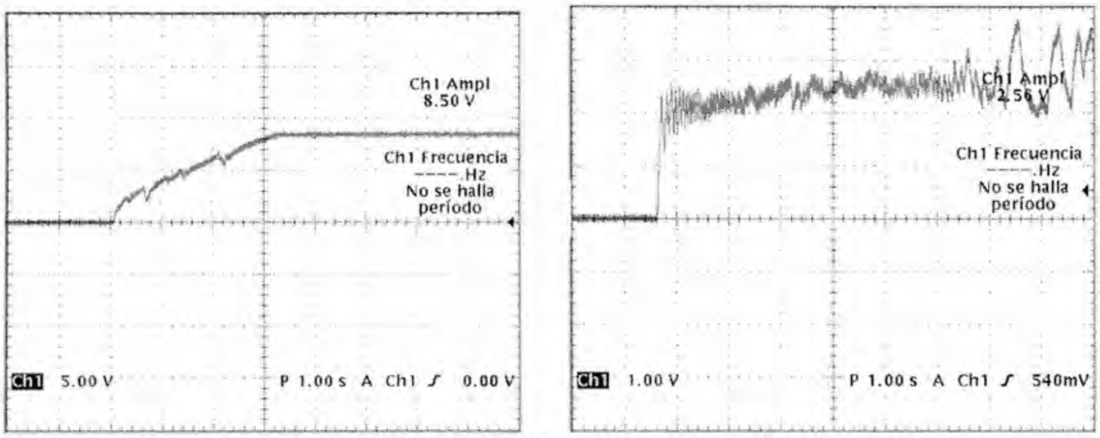


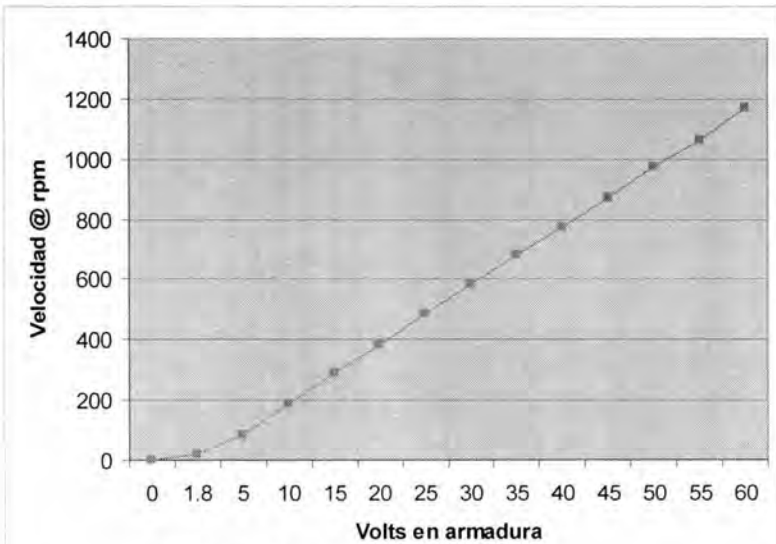
Figura 16. Diagrama del tacómetro construido.

El circuito se utilizo para obtener graficas de velocidad reales del motor en las diferentes pruebas realizadas alimentando el campo con 60 Volts y la armadura con 30 Volts para la primera gráfica, 30 Volts en el campo y 10 Volts en la armadura para la segunda grafica.



Grafica 5, 6. Velocidades medidas con tacómetro

Se realizaron mediciones de velocidad con el tacómetro fabricado y con un tacómetro óptico la curva obtenida al realizar las mediciones de velocidad es la siguiente:



Grafica 7. Curva de Velocidades.

De la curva anterior podemos apreciar que tenemos una no linealidad de zona muerta, por lo que resulta necesario introducir un sistema lineal equivalente en lugar del no lineal. La ecuación no lineal del sistema es:

$$y = 0.002x^2 + 19.443x - 6.1991 \quad (2.2.1.2)$$

Procedimiento de linealización:

$$y - \bar{y} = a(x - \bar{x}) \quad (2.2.1.3)$$

$$a = \frac{\partial y}{\partial x} = 0.004x + 19.443 \quad (2.2.1.4)$$

Evaluamos para el punto:

$$\bar{x} = 20$$

$$\bar{y} = 0.002(20)^2 + 19.443(20) - 6.1991 = 383.46 \quad (2.2.1.5)$$

Sustituyendo en la primera ecuación presentada tenemos:

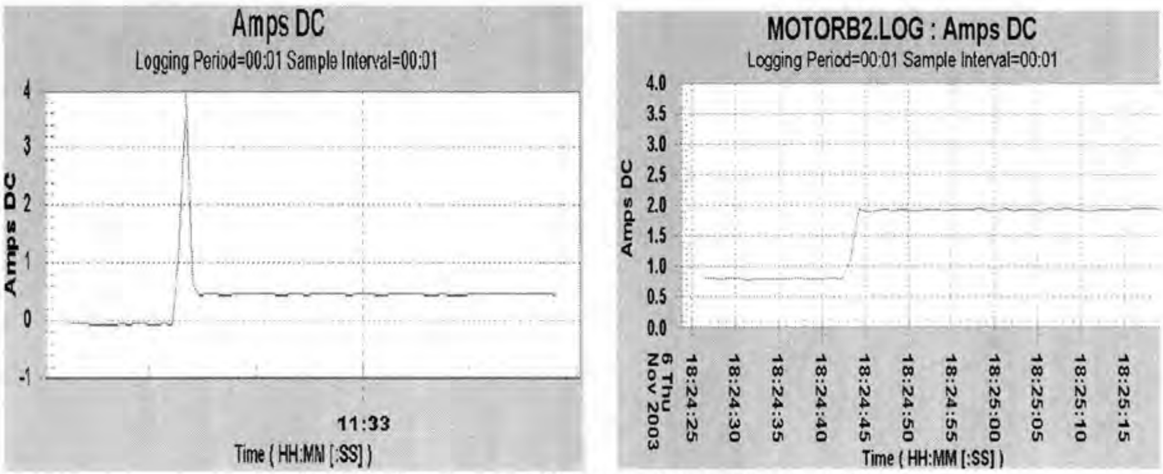
$$y - 383.46 = 0.004x + 19.443(x - 20) \qquad (2.2.1.6)$$

Finalmente la ecuación linealizada es:

$$y = 19.447x - 5.3991 \qquad (2.2.1.7)$$

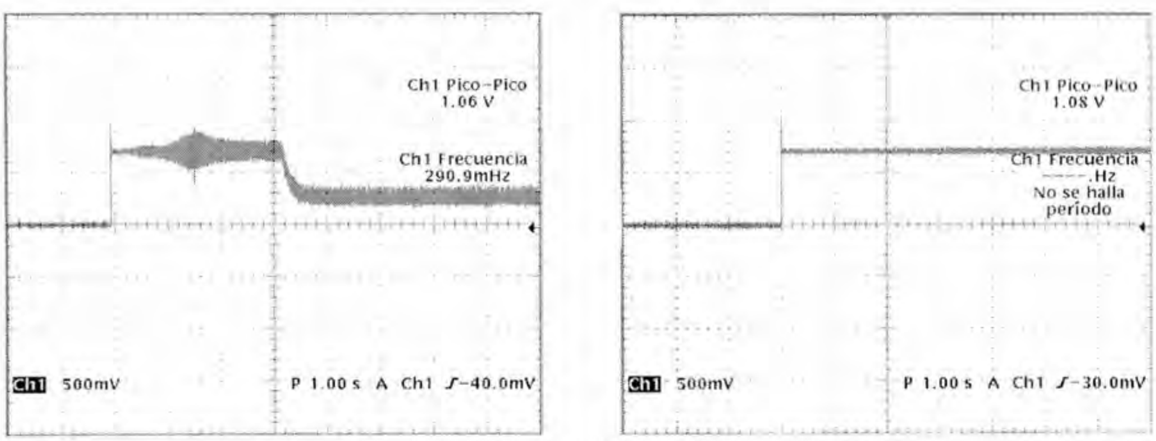
2.2.2 Sensor de Corriente

El primer sensor de corriente usado fue el amperímetro de gancho con que se cuenta en el laboratorio, las graficas que se obtuvieron con este amperímetro se muestran a continuación



Grafica 8, 9. Corriente medidas con el Amperímetro de Gancho

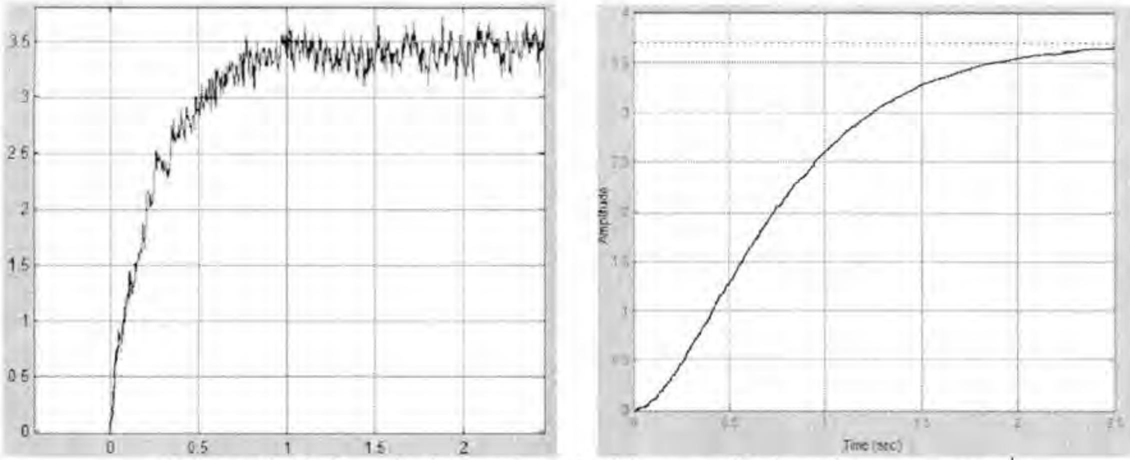
Desafortunadamente las gráficas obtenidas con este amperímetro tienen un período de muestreo muy bajo, por lo que se decidió hacer nuevas pruebas de corriente usando una resistencia de potencia de 1Ω y 10 watts en serie con la armadura, y midiendo el voltaje con el osciloscopio para poder ver la curva, este voltaje es proporcional a la corriente, con esto se obtuvieron las gráficas que se muestran a continuación:



Grafica 10 y 11. *Corriente medida usando resistencia.*

2.3 Caracterización de un motor de CD

Para poder hacer un buen control del motor se deben conocer sus parámetros por lo que realizamos la parametrización de este de forma experimental, en la que se obtuvo la función de transferencia que se muestra a continuación:

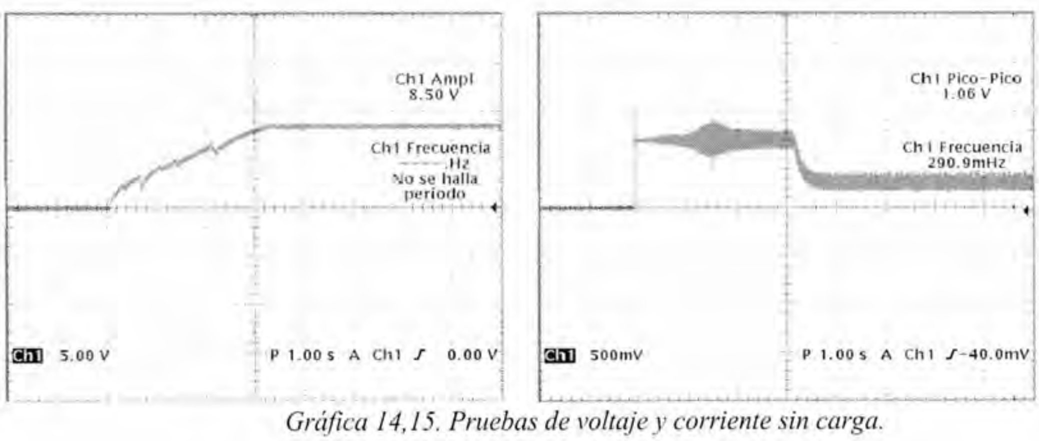


Gráfica 12,13. Función de transferencia del motor y la obtenida por nosotros. [1]

La función de transferencia que obtuvimos es muy similar a la que se obtuvo por medio del tacómetro y nuestra función es:

$$TF = \frac{22.5}{s^2 + 4.933s + 6.082} \qquad (2.3.0)$$

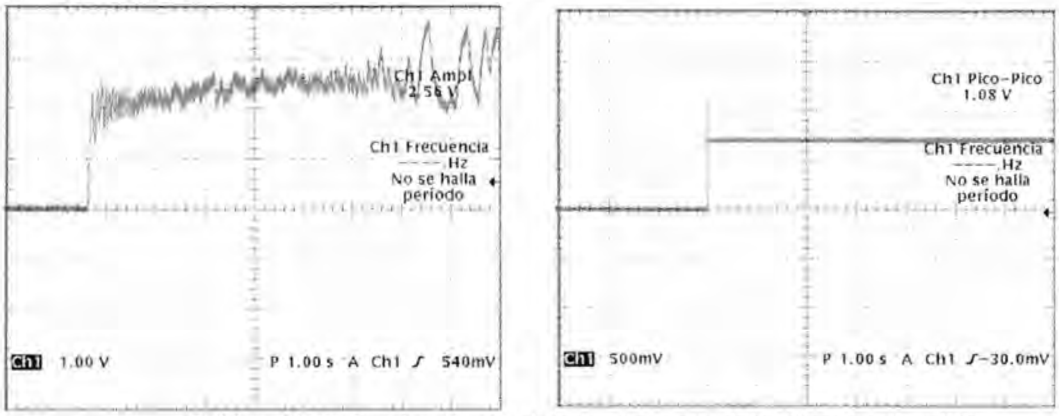
Para hacer la parametrización con este método se hicieron pruebas de voltaje y corriente sin carga en el motor, los resultados fueron los siguientes se puede ver la curva de velocidad gráfica 14, y el pico de corriente que demanda el motor al aplicarle voltaje y después la corriente baja casi instantáneamente y llega a estado estacionario.



Gráfica 14,15. Pruebas de voltaje y corriente sin carga.

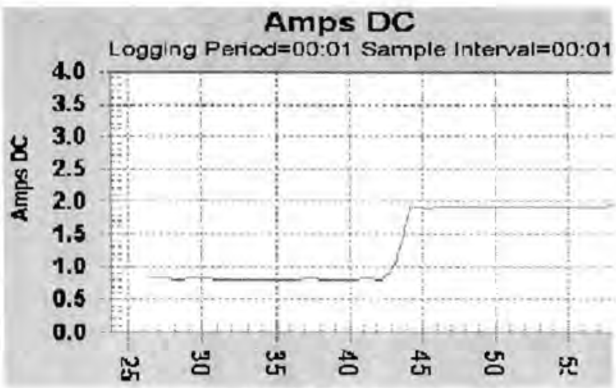
[1] En la gráfica 14 se muestra una curva, los datos de esta curva fueron obtenidos usando un osciloscopio y posteriormente procesados en Matlab.

También se realizaron pruebas de voltaje y corriente con carga que se muestran a continuación:



Gráfica 16,17. Pruebas de voltaje y corriente acoplado el motor al rodillo.

Y se realizó también prueba a rotor bloqueado, los resultado fueron obtenidos con el amperímetro de gancho, en la gráfica se muestra el escalón de corriente, no hay pico pues el rotor esta bloqueado por lo que no demanda mucha corriente al principio.



Grafica 18.Corriente

Por último para empezar a obtener los parámetros del motor, desacoplamos el motor como lo sugiere el libro de la bibliografía usada y el estándar de la IEEE para máquinas eléctricas respectivamente [8] y [15].

Con la finalidad de obtener los parámetros del motor se realizaron las pruebas que sugiere el estándar 113-1985 de la IEEE para máquinas de corriente directa.

Primero se realizó la corrección de las resistencias de Armadura y Campo por el efecto de la temperatura. Debido a que la resistencia de la armadura del motor cambia demasiado debido al aumento de temperatura del motor, se realizó un ajuste en las resistencias de armadura y campo del motor con el objetivo de obtener un valor de resistencias que representara mejor al valor de las resistencias, se usó la siguiente ecuación:

$$R_1 = R_2 \frac{(k + t_1)}{(k + t_2)} \qquad (2.3.1)$$

Donde:

R_1 = Resistencia medida a una temperatura t_1 (temperatura ambiente).
R_2 = Resistencia medida a una temperatura t_2 (25 °C).
k = 234.5 para cobre.
225 para aluminio.

El procedimiento llevado a cabo fue hacer funcionar el motor hasta que alcanzara la temperatura de 25°C, como lo sugiere el estándar de la IEEE, en ese momento se para el motor y se realizaron las mediciones de resistencia nuevamente, así obtuvimos la resistencia que se usó en el simulador de Matlab.

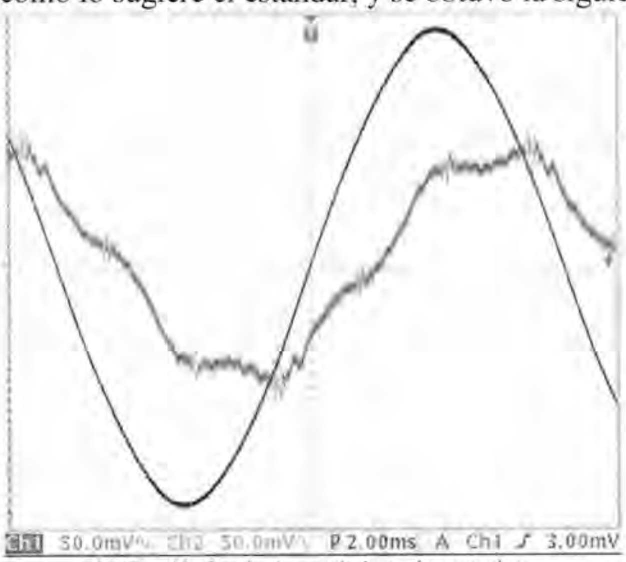
$$R_{2-armadura} = 9.3\Omega \cdot \frac{(234.5+25)}{(234.5+10.54)} = 9.8\Omega \qquad (2.3.2)$$

$$R_{2-campo} = 40.6\Omega \cdot \frac{(234.5+25)}{(234.5+10.54)} = 43\Omega \qquad (2.3.3)$$

Luego se realizaron pruebas para obtener la inductancia del campo y armadura del motor así como el momento de inercia del mismo. Para encontrar la inductancia de la armadura del motor usamos la siguiente relación:

$$L_a = \frac{Vsen\theta}{I2\pi f} \qquad (2.3.4)$$

Se aplicó voltaje de alterna al motor con una amplitud de 20 Volts, corriente de 0.2 A y frecuencia de 60 Hz, como lo sugiere el estándar, y se obtuvo la siguiente gráfica:



Gráfica 19: Corriente y voltaje en la armadura.

En esta gráfica se pueden apreciar dos curvas desfasadas, la curva de mayor amplitud corresponde al voltaje y la otra es la correspondiente a la corriente.

Para calcular el ángulo de desfasamiento de las señales usamos un método gráfico el cual consiste en observar de la gráfica la amplitud de las señales senoidales. Este método nos ahorra el uso de identidades trigonométricas por eso se tomó la decisión de usarlo. De acuerdo con el método gráfico el ángulo de desfasamiento entre dos señales está dado por:

$$\theta = \tan^{-1}\frac{B}{A} \qquad (2.3.5)$$

Las señales de la gráfica podemos expresarlas de la siguiente forma:

$$v\,(t) = v_m sen(\omega t + \varphi)$$

$$v_1(t) = 180x10^{-3} sen(120\pi t) \qquad (2.3.6)$$

$$v_2(t) = 100x10^{-3} sen(120\pi t + \varphi)$$

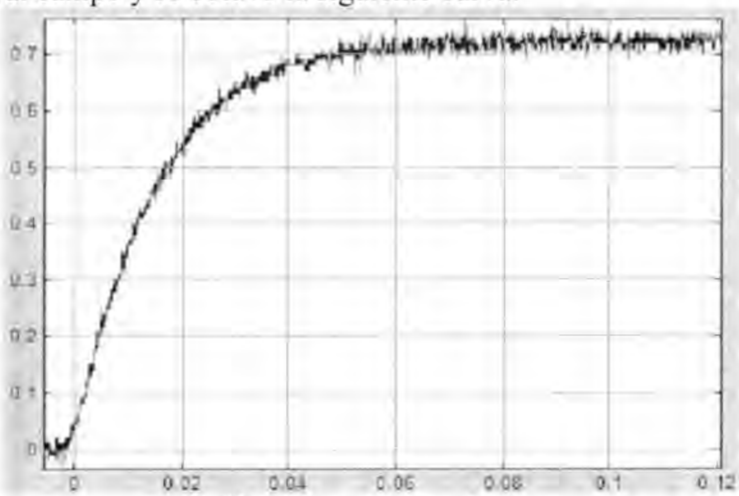
Por lo que B es la magnitud de la señal v_1 y A es la magnitud de la señal v_2

$$\theta = \tan^{-1}\frac{180x10^{-3}}{100x10^{-3}} = 60.94° \qquad (2.3.7)$$

Se obtuvo el ángulo de desfasamiento para poder obtener el valor de la inductancia de armadura se sustituyeron los valores obtenidos en la ecuación 2.3.4:

$$L_a = \frac{20 \cdot sen(60.9454^{o})}{0.2 \cdot 2 \cdot \pi \cdot 60} = 231.8mH \qquad (2.3.8)$$

Para obtener la inductancia del campo se desacopló el motor y se aplico un voltaje de corriente directa al campo y se obtuvo la siguiente curva:



Gráfica 20: corriente en el campo.

En esta gráfica se muestra el valor de estado estacionario de la corriente del campo, este valor corresponde a 0.72 A aproximadamente y se obtuvo el tiempo que tarda en alcanzar el 63.2% de este valor para así usar la siguiente ecuación según el estándar de la IEEE

$$L_c = RT$$

$$L_c = 43 \cdot 0.015 = 750mH \tag{2.3.9}$$

Donde:

R= resistencia de campo, igual a 43 Ω
T= 63.2% de tiempo que tarda en llegar al estado estacionario

Para obtener el momento de inercia según el estándar de la IEEE donde la armadura debe ser colgada como se muestra en la figura:

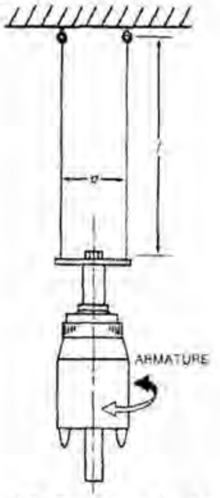


Figura 17. Prueba a la Armadura

Para obtener la inercia (J) se usó la siguiente ecuación:

$$J = \frac{c \cdot m \cdot d^2}{l \cdot f^2} \tag{2.3.10}$$

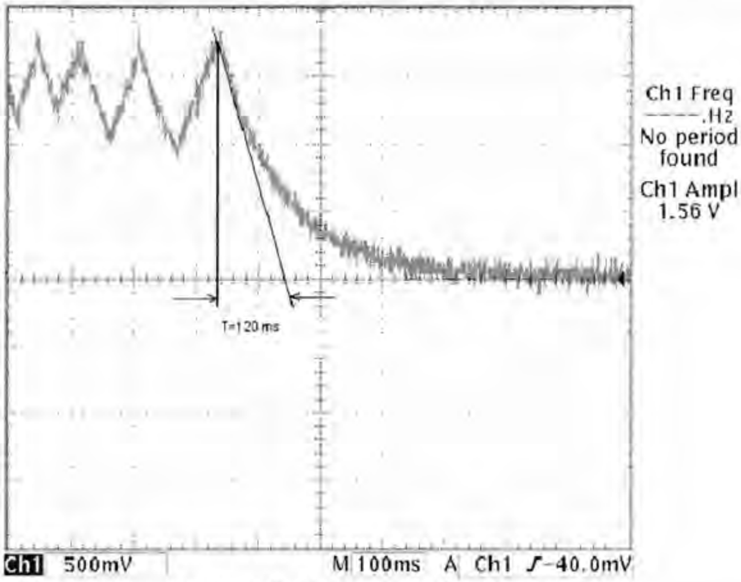
Donde:

c = constante relacionada con las unidades usadas (6.2×10^{-2})
m = masa de la armadura
d = separación entre los cables
l = longitud de los cables
f = frecuencia de oscilación en Hz.

Esto parámetros se obtuvieron al colgar la armadura con cables y medir la separación y longitud de estos, se le aplico una fuerza para que rotara y se midió la frecuencia de oscilación.

$$J = \frac{6.2 \cdot 10^{-2} \cdot 6 \cdot 0.09^2}{0.9 \cdot 10.5} = 0.000319 kg - m^2 \qquad (2.3.11)$$

Para calcular la fricción del motor se excitó al motor con 60 Volts en el campo y con 5 Volts en la armadura y cuando llegó a un estado permanente se le quitó la excitación al motor y se tomó la siguiente gráfica que muestra el tiempo que tarda en pararse el motor



Gráfica 21. Desaceleración del motor

De la curva podemos apreciar que un $T = 120x10^{-3}$ segundos. Ya que teníamos ese valor lo usamos para calcular el valor de la fricción. Para obtener la fricción usamos la siguiente ecuación $\tau_m = \frac{J}{B}$. De la ecuación antes mencionada se despejó B y se sustituyeron los valores de J y el tiempo que se obtuvo de la gráfica que se muestra aquí, J se obtuvo por medio del estándar de la IEEE así obtuvimos que B es:

$$B = \frac{J}{\tau_m} = \frac{319x10^{-6}}{120x10^{-3}} = 2.658x10^{-3} \qquad (2.3.12)$$

Ahora se encontrara la Fem de acuerdo al estándar de la IEEE; sabemos que este voltaje es menor al de entrada de la armadura

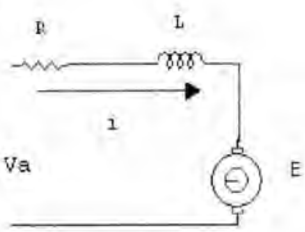


Figura 18. Diagrama

$$V = Ri + L\frac{di}{dt} + E + V_b$$
$$V = RI_a + E + V_b \qquad (2.3.13)$$

Por lo tanto la Fem se obtiene con la siguiente formula:

$$E = V - RI_a - V_b \qquad (2.3.14)$$

Donde:

- E: es la Fem
- V_a: Voltaje de entrada en la armadura
- R_a: Resistencia de armadura con corrección de temperatura
- I_a: Corriente de armadura medida
- V_b: Voltaje por el contacto con las escobillas (carbón, electrografiticas, grafito) sin derivaciones es 3.0 V

Para obtener KΦ es necesario conocer la Fem (E), se conoce la velocidad en radianes pues esa la medimos con un tacómetro láser que mide las revoluciones por minuto y las convertimos a radianes por segundo.

$$E = K\Phi\omega \qquad (2.3.15)$$

Donde:

- E= Fuerza electromotriz
- K= constante de diseño del motor
- Φ= flujo
- ω= velocidad angular

Tomando KΦ como una ganancia Kb y despejándola obtenemos:

$$K\Phi = \frac{E}{\omega} = Kb \qquad (2.3.16)$$

Analizando el siguiente lazo de control se obtendrán los valores de Km, sabemos:

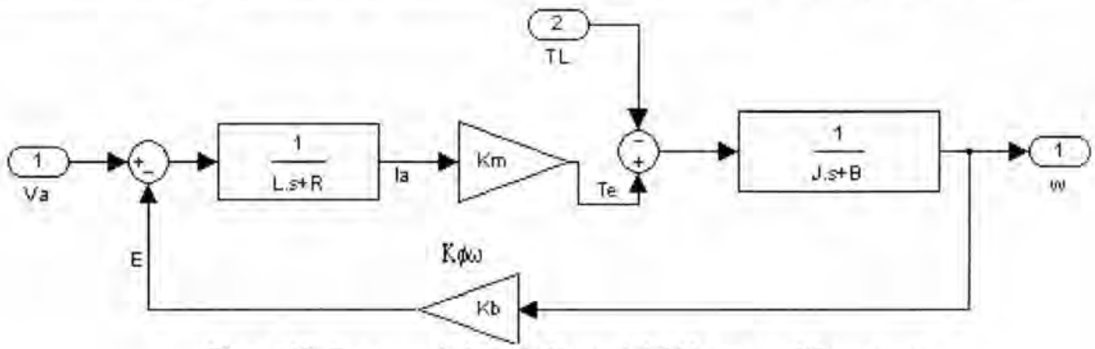


Figura 19. Esquema de lazo de Control del Motor con Vf constante

$$G_\Omega(s)=\frac{\Omega(s)}{V(s)}=\frac{\dfrac{Km}{(Ls+R)(Js+B)}}{1+\dfrac{KmKb}{(Ls+R)(Js+B)}}=\frac{Km}{(Ls+R)(Js+B)+KmKb} \quad (2.3.17)$$

$$Ks=\lim_{s\to 0}G_\Omega(s)=\frac{km}{RB+KmKb}=\frac{\omega_{ss}}{V_{ss}} \quad (2.3.18)$$

$$G_i(s)=\frac{I_a(s)}{V(s)}=\frac{\dfrac{1}{(Ls+R)}}{1+\dfrac{KmKb}{(Ls+R)(Js+B)}}=\frac{(Js+B)}{(Ls+R)(Js+B)+KmKb} \quad (2.3.19)$$

$$Ks=\lim_{s\to 0}G_\Omega(s)=\frac{B}{RB+KmKb}=\frac{I_{ss}}{V_{ss}} \quad (2.3.20)$$

Los valores que se muestran en la tabla son valores que obtuvimos de las mediciones hechas al motor sustituyendo esos valores encontramos valores para Kb y Km, en la simulación en Matlab se usaron los valores promedio de Kb y Km y esto nos da un error máximo de 5%

Vf	Va	Velocidad rpm	Velocidad en rad	Ia	FEM	Kb	Km
60	0	0	0	0.04	-3.392	0	0
60	1.8	17.82	1.86610446	0.28	-3.944	-0.696424036	0.044503
60	5	76.914	8.054408442	0.36	-1.528	0.108611328	0.094734
60	10	167.67	17.55834651	0.39	3.178	0.291041073	0.113898
60	15	258.3	27.0490899	0.44	7.688	0.338983679	0.121057
60	20	345.06	36.13456818	0.48	12.296	0.368522461	0.121598
60	25	435.96	45.65358588	0.51	17.002	0.384456109	0.12469
60	30	522.99	54.76733847	0.56	21.512	0.394592847	0.124599
60	35	611.55	64.04131215	0.57	26.414	0.406340831	0.125275
60	40	694.08	72.68382624	0.63	30.826	0.412655766	0.123238
60	45	783.72	82.07089716	0.7	35.14	0.412765075	0.124312
60	50	875.88	91.72186164	0.73	39.846	0.415510537	0.126039
60	55	957.6	100.2795528	0.78	44.356	0.420528401	0.124226
60	60	1053.9	110.3640567	0.82	48.964	0.441768542	0.11268
					Promedio	0.284565586	0.113911

Tabla 2. Valores Medidos en el motor

En resumen los valores medidos y calculados fueron:

	Campo	Armadura
Resistencia	43 Ω	9.8 Ω
Inductancia	750mH	231.8mH
Inercia	0.000319 kg-m^2	
Fricción	2.65E-03	
Kb	0.2845	
Km	0.1139	

Tabla 3. Valores del Motor

2.4 Investigación

2.4.1 Generadores de CD

No existe diferencia real entre un generador y un motor, salvo el sentido de flujo de potencia. Los generadores se clasifican en cinco tipos principales, de acuerdo con la forma en que se provee el flujo del campo:

1. Generador de excitación independiente: En este generador el flujo es provisto por una fuente separada, independiente del mismo generador.
2. Generador derivación: En el generador derivación se provee el flujo conectando el circuito de campo directamente sobre los terminales del generador.
3. Generador serie: El flujo del generador serie se consigue conectando el circuito de campo en serie con la armadura del generador.
4. Generador con excitación compuesta acumulativa: En el generador de excitación compuesta acumulativa están presentes los campos serie y derivación, y sus efectos son aditivos.
5. Generador con excitación compuesta diferencial: El generador con excitación compuesta diferencial tiene simultáneamente campos serie y derivación, pero sus efectos son sustractivos.

El generador de DC de excitación independiente es un generador cuya corriente de campo es suministrada por una fuente separada de voltaje. En un generador de DC las variables de salida son la tensión en terminales y la corriente de línea.

2.4.2 Modos de operación de una máquina de corriente directa.

En términos del flujo de energía una máquina no solo tiene una entrada y una salida sino que también cuenta con la capacidad de almacenar energía. Esta energía puede ser de la forma de energía magnética en el campo y energía cinética en los componentes rotatorios. Basados en la dirección del flujo de energía podemos identificar dos modos de operación. Se dice que la máquina está trabajando como un motor cuando la energía de una fuente externa conectada a las terminales de su armadura es convertida y se genera trabajo mecánico y/o incrementa la energía cinética del rotor. Se dice que está trabajando como generador cuando la energía de una fuente mecánica impulsora del rotor es convertida en energía eléctrica que sale de las terminales de la armadura a un circuito externo.

Generador

En este modo de operación, una fuente externa de energía mecánica proporciona el par externo aplicado, T_{mech}, que provoca movimiento en el rotor. En la presencia de una densidad de flujo diferente a cero en el entrehierro ya sea debido al magnetismo residual o a la excitación externa, se inducirán voltajes en las bobinas rotatorias del devanado de la armadura. Una corriente, I_{ag}, como se muestra en la figura, fluirá en el devanado de la armadura si el circuito externo que se encuentra conectado a la armadura está cerrado, y entregará potencia de la fem inducida a el resto del circuito de la armadura.

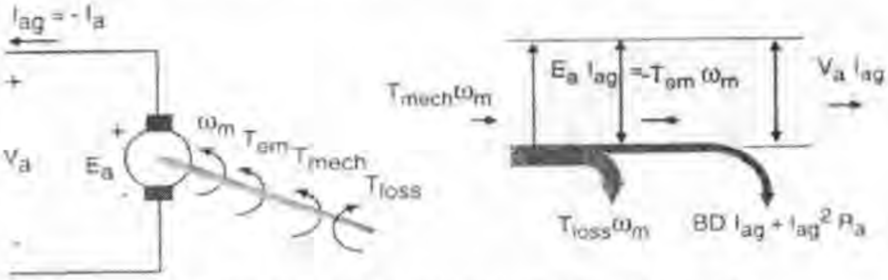


Figura 20. Máquina eléctrica operando como generador.

Las ecuaciones de par y potencia del movimiento rotor pueden se presentan a continuación:

$$T_{mech} - T_{em} - T_{loss} = J\frac{d\omega_m}{dt} \tag{2.4.2.0}$$

$$P_{mech} - P_{em} - P_{loss} = \frac{d(J\omega^2{}_m/2)}{dt} \tag{2.4.2.1}$$

La ecuación de voltaje en el devanado de la armadura para el generador en términos de I_{ag} es la siguiente:

$$E_a = V_a + R_a I_{ag} + V_{brush} + L_{aq}\frac{dI_{ag}}{dt} \tag{2.4.2.2}$$

La ecuación que se presenta arriba sugiere que la potencia fluye del devanado de la armadura al circuito externo que se encuentra conectado a las terminales de la armadura. Si multiplicamos la ecuación anterior por I_{ag} obtenemos lo siguiente:

$$E_a I_{ag} = V_a I_{ag} + R_a I^2{}_{ag} + V_{brush} I_{ag} + \frac{d(L_{ag} I^2{}_{ag}/2)}{dt} \tag{2.4.2.3}$$

A partir de la ecuación anterior podemos encontrar la ecuación que representa el flujo de potencia de la máquina cuando trabaja como generador:

$$P_{mech} - R_a I^2{}_{ag} + V_{brush} I_{ag} + P_{losses} - \frac{d(J\omega^2{}_m / 2 + L_{ag} I^2{}_{ag} / 2)}{dt} = V_a I_{ag}$$

potencia de entrada — pérdidas — cambio en la energía almacenada — potencia de salida

(2.4.2.4)

2.4.3 Regiones Factibles de Par – Velocidad.

Usando la convención de motores, las relaciones entre la fem interna, los voltajes del circuito de la armadura de una máquina de CD operando en estado estacionario con una velocidad del rotor de ω_m, despreciando las pérdidas de las escobillas y usando la relación $T_{em} = k_a \phi I_a$ podemos expresar la velocidad del rotor en términos del par desarrollado como:

$$\omega_m = \frac{V_a}{k_a \phi} - \frac{R_a T_{em}}{k^2{}_a \phi^2} = \omega_{mo} - \frac{R_a T_{em}}{k^2{}_a \phi^2} \qquad (2.4.3.0)$$

En la expresión anterior, ω_{mo} representa la velocidad sin carga cuando $T_{em} = 0$. Cuando V_a, R_a y ϕ se mantienen constantes la expresión de arriba se convierte en una relación lineal entre ω_m y T_{em}. En la figura que a continuación se muestra, podemos ver que en el eje de la velocidad la intersección corresponde a ω_{mo} y podemos apreciar que la pendiente de la línea es proporcional a R_a.

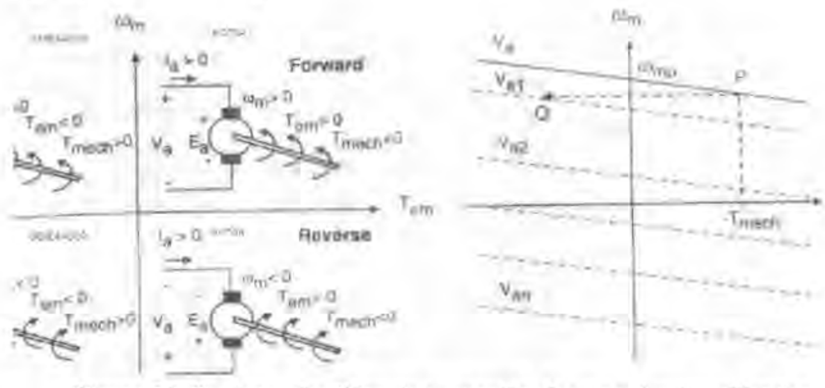


Figura 21. Regiones factibles de operación de una máquina eléctrica.

En la figura anterior se muestra la polaridad y la dirección de las principales variables de interés, esta figura considera la convención para motores con un sentido de rotación en contra de las manecillas del reloj como positivo. En el primer cuadrante es donde se encuentra la máquina eléctrica trabajando como motor. En el segundo cuadrante encontramos que es cuando la máquina trabaja como un generador, en el tercer cuadrante se encuentra que la máquina trabaja como motor, pero en este caso se encuentra operando en reversa; finalmente en el cuarto cuadrante una vez más la máquina opera como generador, pero en reversa. Es importante mencionar que las relaciones $E_a = k_a\phi\omega_m$ y $T_{em} = k\,\phi I_a$ se mantienen verdaderas en términos algebraicos. Cuando se encuentra trabajando la máquina como generador en el segundo cuadrante el T_{em} es negativo. La dirección del par desarrollado es contraria al sentido en el que está girando el rotor. La energía de rotor o el par externo aplicado es convertida por la máquina en energía eléctrica. Si se mantiene el ϕ sin cambiar, la corriente I_a se invertirá, así la dirección del flujo de potencia en el circuito de la armadura también se invertirá.

Cuando la máquina se encuentra trabajando en el segundo cuadrante es común referirse a ésta como freno regenerativo, puesto que el motor desarrolla un par que se opone al incremento de la velocidad. Normalmente encontraremos que cuando la máquina eléctrica se encuentra operando en el segundo cuadrante nos referiremos a ella como generador.

2.4.4 Frenado

El término frenado se refiere a la condición en la que el rotor es desacelerado deliberadamente por algún medio eléctrico. El frenado eléctrico es usado comúnmente para lograr detener la máquina rápidamente en situaciones de emergencia o cuando se tiene que determinar en algún punto exacto. El frenado eléctrico complementa al frenado mecánico reduciendo de esta forma el desgaste en los frenos mecánicos, además que proporciona un frenado más suave y confiable, además que si usamos el freno regenerativo mejoramos la eficiencia de todo el sistema ya que por medio de este método se recupera parte de la energía cinética.

El cambio de motor a frenado puede ser logrado por diferentes medios. El frenado rápido se logra al invertir la polaridad del voltaje aplicado mientras que de manera simultánea se inserta una resistencia externa en el circuito de la armadura para limitar la corriente que circula por ésta. Puesto que la dirección en la que rota y el flujo son los mismos que en el motor, la polaridad del voltaje inducido en la armadura permanecerá igual al del motor. Sin embargo, la dirección de la corriente I_a será contraria a la corriente del motor y con un voltaje aplicado también al contrario obtenemos que la dirección del par T_{em} también será opuesta al sentido de giro del par del motor, esto es, que el T_{em} en el frenado estará en dirección opuesta a ω_m.

La ecuación de voltaje en el devanado de la armadura cuando esta frenando, con el inverso del voltaje de armadura y con la inserción de la resistencia R_{ext} es la siguiente:

$$-V_a = E_a - (R_{ext} + R_a)I_a - V_{brush} - L_{aq}\frac{dI_a}{dt} \quad (2.4.4.0)$$

La ecuación para la potencia a través de la máquina es la siguiente:

$$\frac{d(J\omega^2{}_m/2 + L_{ag}I^2{}_{ag}/2)}{dt} = P_{mech} - V_aI_{ag} - R_aI^2{}_{ag} + V_{brush}I_{ag} + P_{losses} \quad (2.4.4.1)$$

a) Frenado Dinámico

El frenado dinámico se presenta cuando la máquina se encuentra trabajando en el modo de generador y ésta se frena donde el V_a es cero. Este frenado es ampliamente usado en drives eléctricos de tracción. La característica del frenado dinámico en un motor con una excitación fija en el plano par – velocidad es una línea desde el origen puesto que V_a es cero. La pendiente negativa es proporcional a las resistencias de armadura y externa. Un cambio de motor a frenado dinámico puede ser efectuado simplemente al desconectar la fuente de voltaje y reemplazarla con una resistencia de frenado externa en las terminales de la armadura. Con la velocidad del rotor que continua en la misma dirección, el signo de E_a será el mismo. Al remover V_a, ahora la corriente I_a estará circulando por E_a y la máquina operará como generador y la energía cinética del rotor será disipada por medio de las resistencias R_a y R_{ext}.

b) Frenado regenerativo

El frenado regenerativo se refiere al frenado en el que se recupera la energía arriba de la velocidad sin carga, ω_{mo}. Con un voltaje fijo en las terminales,

3. Simulación

Todo lo anterior se presenta en Matlab a continuación

3.1 Fuentes

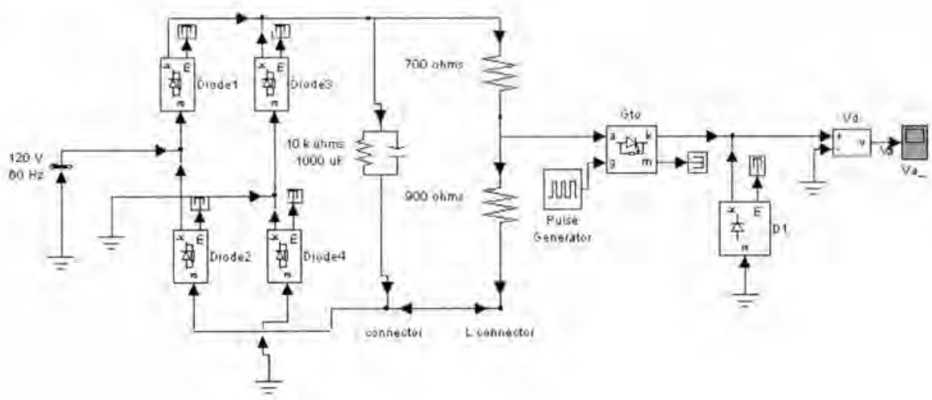
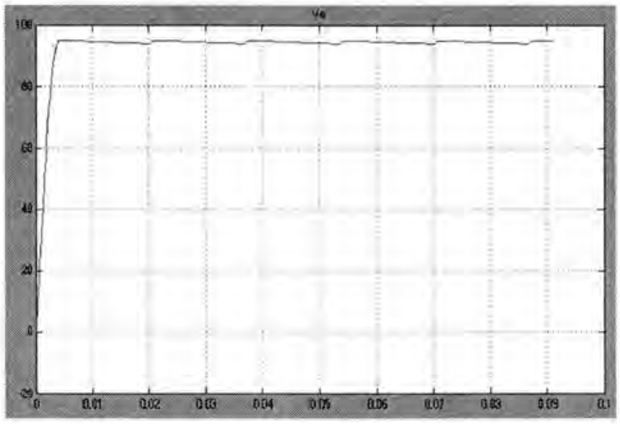


Figura 22. Rectificador para las fuentes



Gráfica 22. Voltaje de armadura

3.2 Modelos del Motor

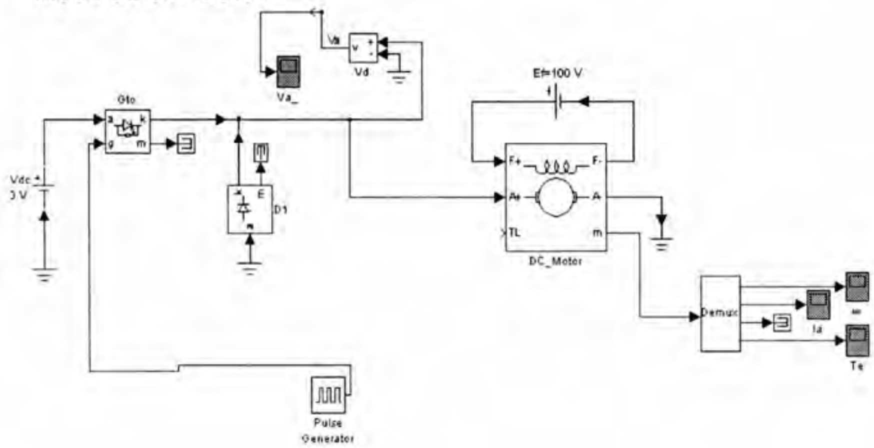


Figura 23. Modelo Demo de Matlab Motor

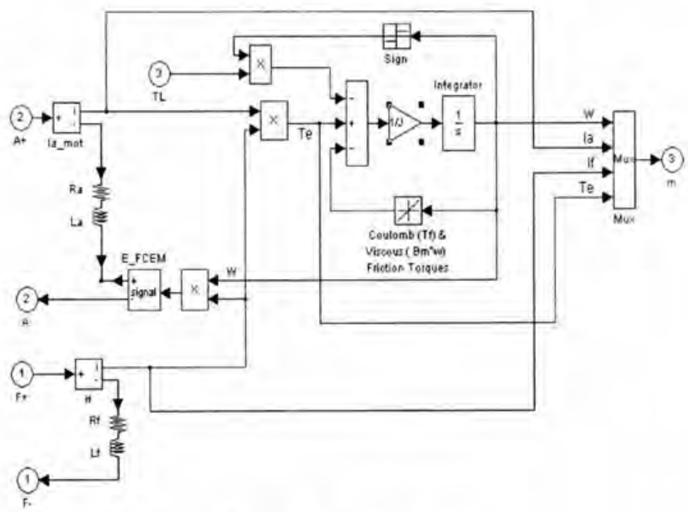
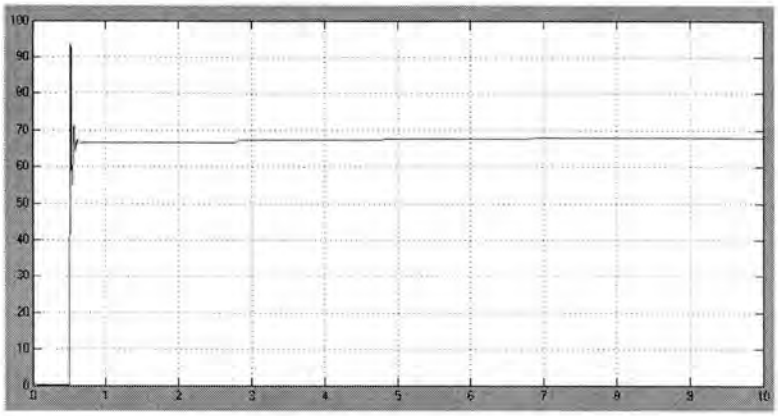
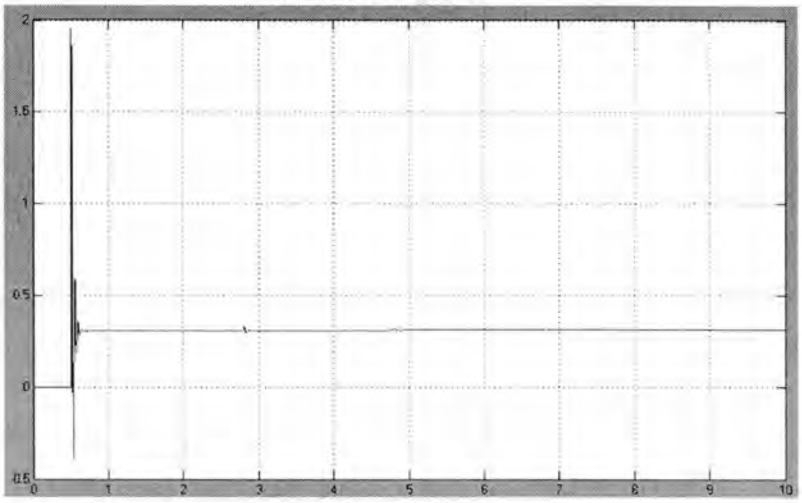


Figura 24. Bloque Motor

A continuación se muestran los resultados preliminares de las simulaciones hechas en Matlab, usando el modelo que se encontró en la librería de demos de Matlab.



Grafica 23. Velocidad w



Grafica 24. Corriente de Armadura

Este modelo demo solo sirvió para hacer pruebas preliminares, desafortunadamente este modelo no sirvió pues lo valores que da la simulación están muy lejos de los medidos.

Por lo tanto con ayuda de nuestro asesor hicimos un modelo del motor, en el cual los valores de la simulación son mas reales tienen una error máximo del 5%, este modelo es el siguiente.

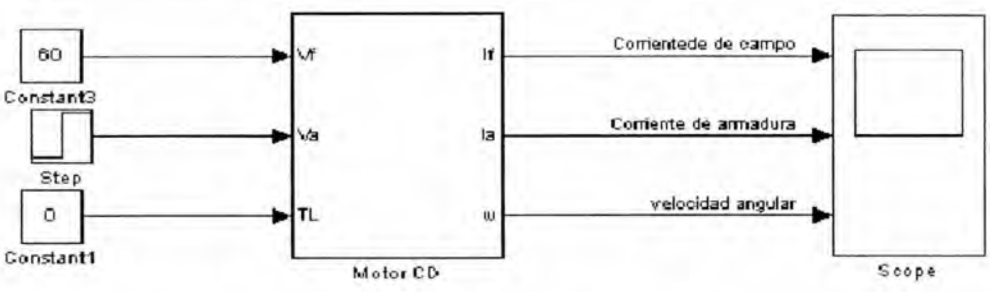


Figura 25. Modelo Motor CD en Matlab

El bloque del Motor CD es el siguiente:

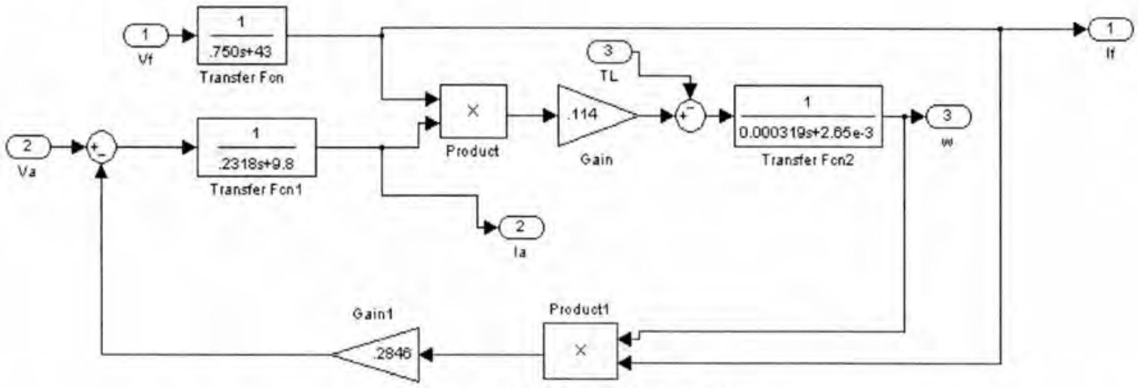
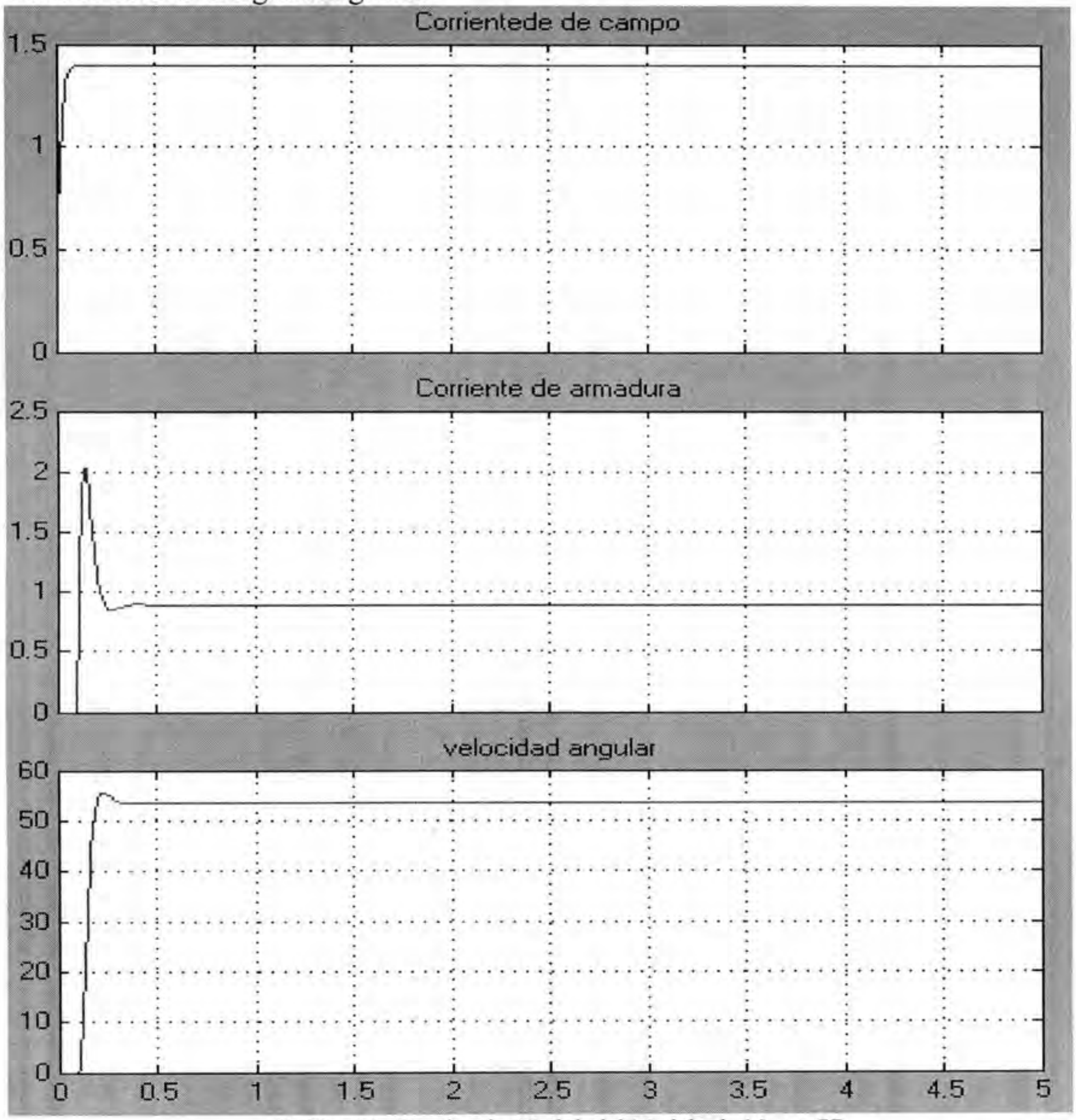


Figura 26. Bloque Motor CD

Aplicando un valor de voltaje de 60 Volts en el campo y variando la armadura de 0 a 60 Volts se obtuvo la siguiente gráfica.



Gráfica 25. Simulación Matlab del Modelo de Motor CD

4. Conclusiones

En este proyecto se integraron muchos de los conocimientos adquiridos en las diferentes materias cursadas a lo largo de la carrera. Aplicando diferentes técnicas y conocimientos de:

Electrónica: De potencia y Analógica
Instrumentación y Mediciones
Actuadores Eléctricos y Control de Motores
Ingeniería de Control
Diseño de Máquinas

La parte principal del proyecto consistió en la caracterización del motor y el desarrollo de la electrónica de potencia e instrumentación. Consideramos que lo más importante fue haber logrado integrar el conocimiento de las áreas mencionadas, en el proyecto para llegar a los resultados obtenidos.

Los objetivos que nos fueron planteados al inicio de este Proyecto de Ingeniería Mecatrónica eran:

1. realizar la instrumentación
2. terminar la etapa de potencia (motor y generador)

Los resultados a los que se llegaron como fue la construcción del tacómetro, lo que un principio no se tenía previsto, originalmente el Prof. Olguín sugirió que podíamos, en caso de que nuestro bolsillo lo permitiera, adquirir tacómetros fabricados con el objeto de no perder tiempo en la realización de un tacómetro y así poder lograr tener un mayor avance en los objetivos planteados del proyecto, para que el tacómetro funcionara nos tomó algún tiempo porque debíamos buscar algunos dispositivos de los que no teníamos idea de cuales usar.

Mediante la caracterización del motor de CD pudimos obtener de manera muy aproximada los parámetros del motor esto parámetros fueron obtenidos gracias al estándar de la IEEE 113-1985 que obtuvimos gracias al Ing. Joel Modragón del IPN, no hicimos uso de la base de datos con la que contamos por que se encuentra limitada, durante el proceso de caracterización surgió el problema de que no podíamos avanzar en la realización de las etapas de potencia, ya que las fuentes deben de ser diseñadas en función de los parámetros del motor. Antes de caracterizar el motor usando el estándar se buscó un método alternativo, usando este método se realizaron pruebas al motor, desafortunadamente los valores obtenidos eran erróneos y se desecharon las pruebas las pruebas.

El siguiente resultado al que se llego teniendo la caracterización del motor, se realizo un modelo en Matlab del motor y se uso un modelo de los demos de Matlab el cual no sirvió por lo que usamos el modelo hecho por nosotros con ayuda de nuestro asesor el Prof. Olguín, este modelo no fue considerado al inicio del proyecto. Al principio, este modelo tenía algunos problemas los cuales fueron detectados cuando se introdujeron los valores del motor obtenidos de las pruebas mencionadas con anterioridad. Gracias a las pruebas realizadas mediante el estándar mencionado anteriormente y a las correcciones realizadas al modelo ahora tenemos el modelo trabajando con un error del 4.7% como máximo.

Lo mas importante acerca de las fuentes es el voltaje, que debe variar de 0 a 100, para hacer funcionar al motor, pues no podemos alimentar al motor con el voltaje nominal pues la corriente que demanda es muy grande y las fuentes solo soportan 6 A es decir, estan diseñadas para hacer funcionar al motor sin carga y acoplado con el rodillo, pues solo resisten 6 A. Para hacer variar el voltaje primero se pensó en usar un PWM lo que implica la construcción de 4 generadores de funciones variar la frecuencia sería un poco mas difícil por lo que nuestro co-asesor el Prof. Castro sugirió el cambio en el diseño de las fuentes, es por esto que para variar el voltaje usamos un modulador Astable al que solo basta cambiarle el valor de las resistencias para que varié el voltaje.

Las pruebas realizadas y las simulaciones demuestran que nuestro modelo de motor en Matlab es muy aproximado a la realidad, el seguir haciendo pruebas acoplando el motor a la bicicleta nos llevaría a obtener mas resultados y demostrar que nuestro modelo es correcto, en las pruebas realizadas para encontrar las fricciones no pudimos acoplar todo el sistema pues el motor no tiene la suficiente fuerza para hacer mover todo el sistema y al ciclista por que demanda mas de 18 A, y nuestras fuentes solo soportan 6 A por lo que se intento hacer las pruebas en el laboratorio de conversión de energía porque en dicho laboratorio se tienen mesas de trabajo que pueden proporcionar hasta 10 A pero aun en el laboratorio las pruebas no se realizaron pues se corría el riesgo de quemas las mesas de trabajo, en lo que consistían estas pruebas era en obtener gráficas de velocidad, con la ayuda de un ciclista de 59kg que empezó a pedalear al momento de aplicarle voltaje al motor y con el amperímetro de gancho medimos que la corriente tenía un pico de 18 A, después de esto el sistema no se estabilizo se mantuvo oscilando entre 9 y 9.45 A, el pico de corriente es lo que puede quemar las mesas de trabajo por lo que las pruebas no se continuaron. Esto nos lleva a la conclusión de que nuestras fuentes deben ser rediseñadas usando dispositivos que soporten 30 A o que el adquirir un motor que tenga mas potencia.

4.1 Trabajo a Futuro y Perspectivas

4.1.1 Diseño de Bicicleta

El modelo de la bicicleta es mecánicamente inestable, lo que provoca que cuando una persona esta montada sobre la bicicleta se pueda caer, por lo que proponemos:

Acoplar unos postes al diseño que mantengan la bicicleta en su lugar y no se mueva de lado a lado cuando esta montada en el rodillo, además de unir el soporte de la bicicleta y el motor y fijar esto al piso. Además fijar la parte delantera de la bicicleta pues ese sale de la base.

4.1.2 Fuentes

Las fuentes armadas y simuladas soportan una corriente máxima de 6 A. Con las pruebas realizadas cuando una persona esta montada en la bicicleta se vio que el motor demanda 18 A, proponemos cambiar los dispositivos que soporten por seguridad 30 A, ó conseguir un motor de más potencia. Como el motor que tiene la bicicleta no tiene tanta potencia demanda más corriente.

4.1.3 Generador

Lo que proponemos cuando el motor hace el cambio a generador, es poner en las fuentes un diodo rectificador, para que no se permita la circulación de corriente en sentido inverso. Esa corriente debe ir a un foco para que se disipe la energía en la resistencia del foco.

4.1.4 Poleas y Banda

Se propone hacer el cambio de las poleas y banda, debido a que las poleas que tiene el motor en este momento no es un sistema reductor de velocidad por que la velocidad máxima de un ciclista es de 60 kmh y el diseño actual entrega una velocidad de 147kmh.

Las bandas planas dependen de la tensión a la que se encuentren entre las poleas, mientras que las bandas en V aprovechan el acuñamiento que existe entre el canal de la polea éstas pierden eficiencia a velocidades medias porque tienden a resbalar. No es necesario usar una banda plana reforzada porque nuestra aplicación no sobrepasa los 500 Hp ni sobrepasa los 50 m/s, además que la distancia entre centros siempre es fija a menos que usen un ajustador de distancia entre centros. Estas bandas tienen una eficiencia del 98% contra 78 a 96% de las V. La mejor banda es una banda de Poliamida o de Uretano ya que tienen fricciones con las poleas de 0.8.
Requisitos del sistema:

Un motor de eléctrico de corriente directa de 1 Hp y 1750 rpm ha de ser utilizado para impulsar a un sistema entrenador estático de ciclismo. Los rodillos que hacen contacto con la rueda trasera de la bicicleta deben girar a una velocidad lineal máxima de (16.6 m/s ó 60 Km/h)[2]. El espacio disponible limita el diámetro de la polea impulsada a 7 cm.

Debido a las limitaciones de nuestro sistema y para aprovechar la estructura con la que se cuenta y no incurrir en gastos de una nueva estructura para el entrenador de ciclismo se planteó la limitante de usar la estructura con la que contamos entonces procedimos a diseñar en base a las dos condiciones de nuestro sistema:

1. Primera restricción: la velocidad lineal máxima que debe tener el rodillo que hace contacto directo con la llanta trasera de la bicicleta es de 16.6 m/s.
2. Segunda restricción: usar la misma estructura lo cual nos limita a usar una polea de 7 cm. de radio como máximo.

Es claro que el diseño actual nos proporciona velocidades muy por arriba de la deseada por nosotros, por eso decidimos cambiar el diseño. Para no entrar en problemas de maquinar poleas el diseño se hizo en base a los valores comerciales de poleas para transmisiones de potencia de banda plana. Debido a las restricciones mencionadas con anterioridad proponemos el siguiente diseño

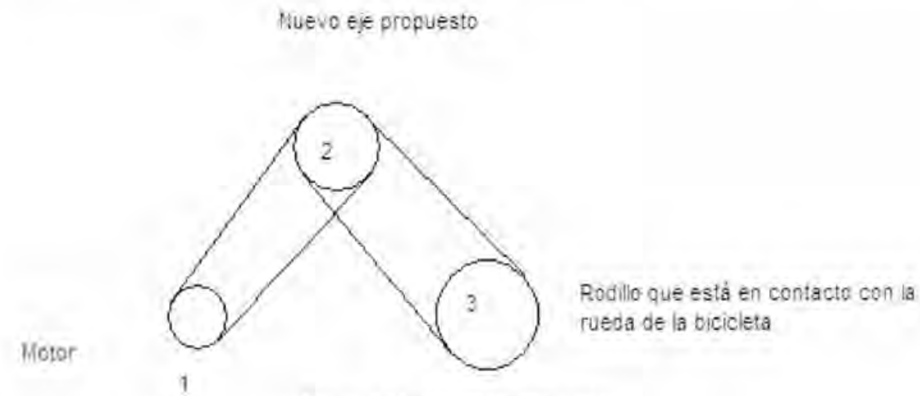


Figura 27. Diseño propuesto.

En la ilustración anterior observamos que la polea de menor tamaño es la del motor, y la más grande la del rodillo en contacto con la rueda de la bicicleta.

Decidimos iniciar el diseño usando la polea de una pulgada de diámetro en la flecha del motor, para después calcular los datos del eje 2 y después del eje 3 con respecto a 2. La velocidad entregada por el motor es de 1750 rpm

$$1750rpm \cdot \frac{2\pi}{60} = 183.26\frac{rad}{s} \qquad (4.1.4.0)$$

[2] De acuerdo con los datos recabados la velocidad media de un ciclista es de 39.6 Km/h por eso se diseño para 60 Km/h.

$$v = \omega \cdot r = \left(183\frac{rad}{s}\right)\cdot 0.0254m = 4.65\frac{m}{s} \tag{4.1.4.1}$$

Ahora en base a esos valores calculamos el diámetro de la polea 2

$$D = d\frac{n_2}{n_1} = 0.0254\cdot\frac{10.65}{4.65} = 0.0581m = 5.81cm \tag{4.1.4.2}$$

El factor de servicio será de 1.2 debido a que este factor depende de las características de la fuente de potencia motriz que proporcionará un impulso de choque mediano. Por eso debemos diseñar para transmitir una potencia de

$$H = 1Hp(1.3) = 1.3Hp \tag{4.1.4.3}$$

Pero en este caso decidimos usar la una polea de 6 cm de diámetro por ser el valor de polea comercial más cercano a este valor. Para realizar los cálculos de longitud de banda tomamos una distancia entre centros de 0.4, cabe mencionar que este es un valor tomado aleatoriamente por nosotros.

$$L = \left[4C^2 - (D-d)^2\right]^{1/2} + \frac{1}{2}(D\theta_D - d\theta_d) = 29.13in \tag{4.1.4.4}$$

$$\theta_d = \pi - 2sen^{-1}\frac{D-d}{2C} = 3 \tag{4.1.4.5}$$

$$\theta_D = \pi + 2sen^{-1}\frac{D-d}{2C} = 3.2 \tag{4.1.4.6}$$

Estas poleas seleccionadas anteriormente cumplen con el diámetro mínimo de poleas para que tengan una fricción del 0.8% entre las poleas y la banda, la distancia entre centros es de 0.4 m y es fija. Se debe comprar una banda plana de espesor de $t = 0.11in$ y debe ser una banda de Poliamida con una especificación A-2 y que cuente con revestimiento de fricción de caucho acrilonitrilo-butadieno en ambos lados. Ahora calculamos para el eje 3

$$D = d\frac{n_2}{n_1} = 0.06\cdot\frac{16.65}{10.65} = 0.0938 = 9.38cm \tag{4.1.4.7}$$

$$L = \left[4C^2 - (D-d)^2\right]^{1/2} + \frac{1}{2}(D\theta_D - d\theta_d) = 49in \tag{4.1.4.8}$$

$$\theta_d = \pi - 2sen^{-1}\frac{D-d}{2C} = 2.53 \tag{4.1.4.9}$$

$$\theta_D = \pi + 2sen^{-1}\frac{D-d}{2C} = 3.74 \tag{4.1.4.10}$$

Por lo que se propone una banda de poliamiada F- 2 con un espesor de 0.07 in que tiene un coeficiente de fricción de 0.8 con las poleas

4.3 Comentarios

Lo mas importante en este proyecto de Ingeniería Mecatrónica es que fuimos capaces de incorporar muchos de los conocimientos acerca de diferentes materias durante el proyecto y no solo eso, si no que además fuimos capaces de ser autodidactas y por lo mismo aprender muchos durante la realización del proyecto.

Además de que el proyecto realizado fue un reto para nosotros que tal vez no se cumplió por completo pero estamos seguros de que lo realizado llevo mucho esfuerzo y trabajo, trabajo durante el cual hubo muchos momentos desagradables pero también hubo muchos agradables pues el proyecto nos pareció desde el principio muy interesante sobre todo por la aplicación que tiene, tal vez al principio no pusimos todo nuestro esfuerzo en él, debido a que nos estábamos acoplando como equipo pero después el proyecto llego a ser cada vez mas de nuestro agrado y como en todo proyecto le dedicábamos la mayor parte de nuestro tiempo.

Agradecemos al Ing. Joel Mondragón por habernos proporcionado el estándar de la IEEE 113-1985, al Dr. Pedro Ponce por permitirnos realizar muchas pruebas en el laboratorio de conversión de energía, a nuestro co-asesor M. en C. Marco A. Castro que nos ayudo mucho en la parte de la electrónica, y a nuestro asesor Dr. Ernesto Olguín por su ayuda.

5. Bibliografía

[1] Proyectos de Ingeniería 2 "Entrenador Estático de Ciclismo" Noviembre 2001, Murena Lavín Martínez, Iván A. Centeno García, Mitzi Sánchez Galicia, Lilyana Herrera Moreno, Abel Sánchez Gutiérrez.
[2] Reporte Final, "Bicicleta Virtual", Proyectos de Ingeniería Mecatrónica I, Semestre Agosto-Diciembre 2003.
[3] Ogata, K., *Ingeniería de Control Moderna*, Ed. Prentice Hall.
[4] Franklin, G. & Powell, *Feedback Control of Dynamic Systems*, 6a edición, Ed. Addison Wesley.
[5] Mohan Ned, Undeland Tore, *Power Electronics converters, applications, and design*, 2nd Edition, John Wiley & Sons, Inc. New York 1995.
[6] Webster, G. John. *Electrical and Electronics Engineering*. Volume 21. John Wiley & Sons Inc. 1999, USA. 355,369
[7] Limón Robles, Jorge. *Manual del curso de instrumentación y Mediciones*. Primera Edición. 2002. México.
[8] Rexford, Kenneth B. *Electrical Control for Machines*, 4th ed. Delmar Publishers Inc. 1992.
[9] Chee-Mun Ong. *Dynamic Simulations of electric machinery using Matlab/Simulink.* Prenti

[10] Chapman, Stephen J. *Máquinas Eléctricas*. Ed. McGraw Hills 3ra. Edición, Santa Fe de Bogotá.
[11] Aguirre Esponda, Guillermo. *Diseño de Elementos de Máquinas*. Editorial Trillas: UNAM, Facultad de Ingeniería, México 1990.
[12] Shigley, J. Edward, Mischke R. Charles. *Diseño en Ingeniería Mecánica*. 5 Edición, Mc Graw Hill, México 1990.
[13] Dorf, Richard C; Bishop, Robert H. *Modern Control Systems*. Addison- Wesley Publishing Group. 7 Edition, USA1995.
[14] Alexander, Charles K; Sadiku, Matthew. *Fundamentals of Electric Circuits*. Mc Graw-Hill. International Edition. USA 2000.
[15]IEEE Std 113-1985, IEEE Guide: Test Procedures for Direct-Current Machines
[16] Prácticas de Laboratorio de Control de motores del Dr.Pedro Ponce Cruz.
[17] Apuntes de clase Electrónica Aplicada del M en C. Marco Castro
[18] Software Pspice.
[19] Software Power Log.
[20] Haptics http://whatis.techtarget.com/definition/0,,sid9_gci212226,00.html
[21] Ciclismo http://www.ctv.es/USERS/docjimenez/ciclismo.html
[22] TACX http://www.tacx.nl/
[23] ELITE: http://www.elite-it.com/
[24] CATEYE: http://www.cateye.com/
[25] MINOURA: http://www.minoura.co.jp/
[26] CARDGIRUS http://www.cardgirus.com

A N E X O S

A.1

IEEE Guide: Test Procedures for Direct-Current Machines

IEEE Std 113-1985
(Revision of IEEE
Std 113-1973)

IEEE Guide: Test Procedures for Direct-Current Machines

Sponsor

Rotating Machinery Committee of the
IEEE Power Engineering Society

Secretariat

Institute of Electrical and Electronics Engineers
National Electrical Manufacturers Association

The Institute of Electrical and Electronics, Inc
345 East 47th Street, New York, NY 10017, USA

IEEE Standards documents are developed within the Technical Committees of the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Board. Members of the committees serve voluntarily and without compensation. They are not necessarily members of the Institute. The standards developed within IEEE represent a consensus of the broad expertise on the subject within the Institute as well as those activities outside of IEEE which have expressed an interest in participating in the development of the standard.

Use of an IEEE Standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least once every five years for revision or reaffirmation. When a document is more than five years old, and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of all concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason IEEE and the members of its technical committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE Standards Board
345 East 47th Street
New York, NY 10017
USA

Foreword

(This Foreword is not a part of IEEE Std 113-1985, IEEE Guide: Test Procedures for Direct-Current Machines.)

This standard is a revision of IEEE Std 113-1973, Test Code for Direct-Current Machines. A title change has been incorporated into the revision to be similar to other standards of this type. The title is now IEEE Guide: Test Procedures for Direct-Current Machines.

The institute wishes to acknowledge its indebtedness to those who have freely given of their time and knowledge in the preparation of this revision. Appreciation is also expressed to their employers, whose cooperation is essential in a volunteer effort such as this.

This revision was prepared and approved by a working group of the Direct-Current Machinery Subcommittee of the IEEE Rotating Machinery Committee, and at the time of this revision had the following membership:

F.T. DeWolf, *Chairman*

H.B. Hamilton
E.F. McBrien
D.C. Morton
J.D. Raba
J.B. Salay
L.A. Schlabach
E.J. Silva
J.V. Stude
V.E. Vrana
W.P. Willendrup
E.J. Woods

At the time this standard was approved, the Direct-Current Machinery Subcommittee of the IEEE Rotating Machinery Committee of the IEEE Power Engineering Society had the following membership:

E.J. Woods, *Chairman*

F.S. Buchwald
O.C. Coho, Jr
F.T. DeWolf
J.S. Ewing
E. Fuchs
H.B. Hamilton
W. Lord
R.E. Lordo
C.H. Merrifield
E.H. Myers
E.P. Priebe
J.E. Radcliffe
J.B. Salay
L.A. Schlabach
E.J. Silva
E.P. Smith
J.V. Stude

When the IEEE Standards Board approved this standard on September 22, 1983, it had the following membership:

James H. Beall, *Chairman*
Edward Chelotti, *Vice Chairman*
Sava I. Sherr, *Secretary*

J.J. Archambault
John T. Boettger
J.V. Bonucchi
Rene Castenschiold
Edward J. Cohen
Len S. Corey
Donald C. Fleckenstein
Jay Forster
Donald H. Heirman
Irvin N. Howell
Joseph L. Koepfinger*
Irving Kolodny
George Konomos
John E. May
Donald T. Michael*
John P. Riganati
Frank L. Rose
Robert W. Seelbach
Jay A. Stewart
Clifford O. Swanson
Robert E. Weiler
W.B. Wilkens
Charles J. Wylie

*Member emeritus

Contents

IEEE Guide: Test Procedures for Direct-Current Machines

> WARNING: *Because of the dangerous current, voltages, and forces encountered, adequate safety precautions should be taken in all tests to avoid damage to equipment and injury to personnel. No attempt is made here to list or review the manifold general safety precautions which are well established throughout the industry. However, these test procedures do recommend special safety precautions applicable to the particular test described. All tests should be performed by knowledgeable and experienced personnel.*
>
> *The IEEE working group and committee members having voluntarily devoted time and knowledge to benefit the electrical industry in creating and revising this specification, disclaim all responsibility for its use and application.*

1. Scope

These test procedures include recommendations for conducting and reporting generally acceptable tests to determine the performance characteristics of conventional direct-current machines. The tests are in two categories as described in 1.1 and 1.2.

1.1 Tests of Direct-Current Motors and Generators Designed for Essentially Ripple-Free Operation. For operation to be classed as ripple-free in accordance with this test procedure, the peak-to-peak value of the alternating component of the current shall be less than 6%, or the rms value less than 2%, of the rated current of the test machine at any of the test conditions provided that the lowest alternating frequency component of the current is 50 Hz or greater.

1.2 Tests of Direct-Current Motors Designed for Use with Rectifier Power Supplies. When a test procedure applies to a dc motor supplied with rectified power not meeting the essentially ripple-free criteria of 1.1, the procedure will be identified by the following opening statement: "On rectified power . . ."

A brief bibliography of technical papers relating to the operation of dc motors on rectified power is located in Section 8.

1.3 Other Test Procedures. It is recognized that there may be test procedures other than those described herein. When more than one procedure can be used, local conditions and the degree of precision desired will determine the procedure to be used. This guide shall not be interpreted or construed as requiring the performance of any or all of the tests herein, in any given transaction.

1.4 References

[1] ANSI C63.4-1981, American National Standard Methods of Measurement of Radio-Noise Emissions from Low-Voltage, Electrical and Electronic Equipment in the Range of 10 kHz to 1 GHz.[1]

[2] ANSI/IEEE Std 4-1978, IEEE Standard Techniques for High-Voltage Testing.[2]

[3] ANSI/IEEE Std 43-1974 (R 1981), IEEE Recommended Practice for Testing Insulation Resistance of Rotating Machinery.

[4] ANSI/IEEE Std 100-1984, IEEE Standard Dictionary of Electrical and Electronics Terms.

[5] ANSI/NEMA MG1-1978, Motors and Generators.[3]

[6] IEEE Std 85-1973 (R 1980), IEEE Standard Test Procedure for Airborne Sound Measurements on Rotating Electric Machinery.

[7] IEEE Std 118-1978, IEEE Standard Test Code for Resistance Measurement.

[8] IEEE Std 119-1974, IEEE Recommended Practice for General Principles of Temperature Measurement as Applied to Electrical Apparatus.

[1] ANSI documents are available from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

[2] IEEE documents are available from IEEE Service Center, 445 Hoes Lane, Piscataway, NJ 08854.

[3] NEMA documents are available from the National Electrical Manufactures Association, 2101 L Street, NW Washington, DC 20037.

2. Tests

2.1 General. The tests in this guide used to check the performance of direct-current machines are divided into four general categories:

(1) Preliminary tests (see Section 4)

(2) Performance determination tests (see Section 5)

(3) Temperature test (see Section 6)

(4) Miscellaneous tests (see Section 7)

The preliminary tests include not only those tests incorporated in the group of static tests (see 2.1.1), but, in addition, those tests usually conducted before the performance determination test can or should be undertaken. The performance determination tests and temperature test are those usually made to determine the performance of a direct-current machine. Miscellaneous tests are often undertaken to provide additional information pertaining to a specific dc machine.

Direct-current machines are usually tested at the point of manufacture (see 4.1.1). Certain tests from each of the four general categories are frequently incorporated into three groups of tests to serve as a guide, but these three groups do not necessarily constitute standard tests.

2.1.1 Static Test. The static test usually includes:

(1) Resistance measurement of windings (4.2)

(2) Air gap measurements (4.3)

(3) Polarity and impedance drop of shunt-field coils (4.4)

(4) Electrical resistance of insulation (cold) (4.7)

(5) High-potential test (4.8)

2.1.2 Complete Test. See Form A. The complete test usually includes the static test (see 2.1.1) and the following tests:

(1) Vibration (4.5)

(2) Magnetic saturation (5.1)

(3) Commutation (5.2)

(4) Regulation (5.3)

(5) Efficiency and Losses (5.4), (5.5), (5.6)

(6) Temperature tests (6)

2.1.3 Routine Test. Routine tests are often listed in a specific standard applying to a particular type or size of dc machine. See Form B.

2.2 Alternative Methods. For many of the tests, alternative methods are described that are appropriate for the different size and types of direct-current machines and for the different conditions encountered during the test. In some cases, the preferred test method is indicated.

3. Electrical Measurements and Power Sources for All Test Procedures

3.1 Instrument Selection Factors. Either analog or digital-type instruments may be used in testing. Factors affecting accuracy, particularly with nonelectronic, analog instruments are: loading of the signal source, lead calibration, and the range, condition, and calibration of the instrument. Since instrument accuracy is generally expressed as a percent of full scale, the range of the instrument chosen should be as low as practical. The instrument should bear record of recent calibration and if extreme importance is attached to the test results the instrument should be calibrated immediately before and after the completion of the test procedure. When several instruments are connected in the circuit simultaneously, additional corrections of the instrument indication may be required.

Electronic instruments are generally more versatile and have much higher input impedances than passive (nonelectronic) types. Higher input impedance reduces the need to make corrections for the current drawn by the instrument. However, high input impedance instruments are more susceptible to noise. Common sources of noise are: inductive or electrostatic coupling of signal leads to power systems, common impedance coupling, or ground loops, inadequate common-mode rejection, and conducted interference from the power line. Good practice requires the use of shielded twisted pairs for signal leads, grounding of the shield at only one point, and keeping signal cables as far away as possible from power cables. All exposed metal parts of these instruments should be grounded for safety. Instrument calibration requirements are similar to those of nonelectronic instruments.

When suitable automatic data-acquisition systems or high-speed recorders are available they may be used provided they are suitable for the pulsating nature of the signals arising from operation on rectifier power supplies.

3.1.1 On rectified power, the average or dc values of armature and field voltages and current can be measured using permanent-magnet moving-coil (d'Arsonval) type instruments, or other instruments, including digital instrumentation known to provide true average readings. Root-mean-square values can be measured with electrodynamometer-type, iron-vane-type, or other instrument types including digital instrumentation known to provide true rms readings. Alternating-current instruments of the type using rectifiers so as to sense only a portion of the voltage or current signal and instruments which are calibrated based on the assumption of a sinusoidal wave shape should not be used. Oscilloscope observations of the voltage and current signals are recommended to ensure that the waveforms are of the shapes to be expected. Suitably low-inductance current transducers and shielded leads should be used to minimize signal distortion and eliminate extraneous voltages.

3.1.2 The ac component of the armature and field voltages and current can be measured separately using suitable instrumentation and combined with the average value to yield the rms value of the variable. For example, the component values of the armature current are interrelated:

$$I_{rms} = \sqrt{I_{dc}^2 + I_{ac}^2}$$

where

I_{rms} = rms value of the current
I_{dc} = average value of the current
I_{ac} = rms value of the ac component of the current

If a current transformer is used to block the dc component of the current, it should be of sufficient size to avoid magnetic saturation resulting from the direct current passing through the primary winding. If a dc bias winding is used to avoid magnetic saturation of the transformer, means should be taken to restrict ac ampere turns in the bias winding to less than 2% of the ac ampere turns in the primary windings. The magnitude, wave shape, and phase relationship of the secondary current should be observed with an oscilloscope and compared with the primary current.

If a capacitor is used to block the dc component of voltage, it should be of sufficient size so that the ac voltage drop across the capacitor is less than 2% of the ac component of the voltage measured.

3.2 Voltage Measurement. Machine voltage measurements should be taken with the signal leads connected to the machine terminals. If local conditions will not permit such connections, the error introduced should be evaluated and the readings corrected.

Tests should be made at as near rated voltage as practical. If terminal voltage is slightly different from rated voltage, this difference shall be taken into account and corrections made in calculating machine characteristics.

On rectified power, the input ac voltage to the rectifier should be the specified value, +2%, −0%.

3.3 Current Measurement. Where the current to be measured is within the range of available ammeters, an ammeter may be inserted directly into the circuit. Current transducers are used when the range of available ammeters is exceeded. Also, isolation amplifiers may be used for safety purposes and to be compatible with other instrumentation. In all cases, the impedance of the ammeter or transducer shall not appreciably affect the characteristics of the machine or the circuit tested.

The current required by all protective devices used during the test shall not appreciably affect the test results. This guide recommends that these devices be so connected that a minimum of correction is necessary.

On rectified power, the rms value of the armature current or the ac component of the armature current, or both, should be measured.

3.4 Power Measurement. Electric power (watts) is usually computed as the time average of the instantaneous product of voltage and current. A direct-reading wattmeter may be used. If very high accuracy is required, corrections should be made for power loss in instruments, test connections, and protective devices.

If a calibrated driving motor or cradled dynamometer or torquemeter is used in loss measurements it should preferably be of such a size that it is loaded to at least one-third of its rating when losses for rated load are measured.

3.4.1 Input Armature-Circuit Power. On rectified power, input armature-circuit power may be measured directly using a true-reading wattmeter or other measurement means wherein the instantaneous product of voltage and current is time averaged. Alternatively, the dc and ac power components may be measured separately as described in (1) and (2) below and added together.

(1) The dc component of armature circuit power input is the product of the average input armature circuit voltage and current as measured with average-reading instruments.

(2) The ac component of the armature cir-

cuit power input is the average value of the product of the instantaneous ac components of the armature circuit voltage and current. It may be measured by blocking the dc component of either the voltage or current signals passing to the power measurement means. The precautions described in 3.1.2 relating to the fidelity of voltage and current signals apply to these signals at the power measurement means. In addition, it should be determined by simultaneous oscilloscope observations that the current and voltage signals are repetitive and precise in their phase relationship.

3.4.2 Input Shunt-Field Power. The input shunt-field power can usually be taken with sufficient accuracy as the product of the average shunt-field voltage and current. If the shunt-field current is not ripple-free as defined in 1.1 the shunt-field power shall be calculated as the product of the square of the rms value of the shunt-field current and the dc resistance.

3.5 Power Sources

3.5.1 Direct-Current Supply. The power supply should be such that a minimum of adjustment is necessary during the time test readings are taken. In general, it should be of sufficient size and in such a condition that its operation does not influence the machine under test. The power supply should be essentially ripple-free as defined in 1.1.

3.5.2 Rectified Alternating Current Supply. Performance and conformance tests on dc motors intended for service with rectifiers should be conducted using a power supply of the type resulting in the amount and frequency of current ripple for which the motor is designed. The voltage and current waveforms should be of the expected shapes and free from disturbances and instabilities. The difference between the highest and lowest peak amplitudes of the current pulses over one cycle of the fundamental frequency should not exceed 2% of the highest pulse amplitude. Significant rectifier parameters regarding armature current ripple are: number of phases and circuitry, input ac voltage and frequency, and armature circuit inductance and resistance. In the absence of rectifier facilities meeting these requirements, and when so noted on the test data record, an armature circuit power supply providing the same frequency but more current ripple than expected in service may be used and the ripple restricted to the rated value using a smoothing choke.

When so noted on the test-data record, a direct current power supply having a low-ripple voltage content, such as a dc generator, may be used to supply the shunt-field circuit power during tests using a rectifier to supply the motor armature circuit.

An indication of motor heating can be obtained from tests using dc armature power having a low-ripple content, such as a dc generator, by maintaining the armature current at the anticipated rms value in rectifier service. However, it should be recognized that machine temperatures may be higher in actual rectifier service, particularly in the case of enclosed machines. Such tests do not measure commutation performance. A low-ripple dc supply may also be used in conducting loss separation tests and in taking comparative heating and commutation tests.

4. Preliminary Tests

4.1 Reference Conditions

4.1.1 Location for Tests. Tests are usually made at the plant of the manufacturer, unless an otherwise mutually agreed upon location is established.

4.1.2 Ambient Air. Unless otherwise agreed upon, the surrounding air temperature should be between 10 °C and 40 °C, and the altitude should not exceed 1000 m (3300 ft). The procedure to be followed in the measurement of ambient temperature is given in IEEE Std 119-1974 [8][4].

4.1.3 Terminal Markings. Terminal markings should be in accordance with ANSI/NEMA MG1-1978 [5]. However, the manufacturers' diagram of connections should be the authority for checking terminal markings and polarities.

4.1.4 Direction of Rotation. When the direction of rotation is not specified, motors shall be tested with counterclockwise rotation and generators with clockwise rotation, when viewed from the commutator end.

4.1.5 Test Machine Rating. In these test procedures by *rated load* is meant rated load current.

4.2 Winding Resistance Measurements. The resistance of the machine windings is determined so as to check the completed winding connec-

[4] Numbers in brackets correspond to those of the references in 1.4 of this standard.

tion, to calculate the I^2R loss, and to establish a reference resistance at a reference temperature to be used in the determination of the average temperature of the winding. (For the last of these purposes a portion of the winding may be used rather than the complete winding. See 6.3.1.2).

Resistance measurement should be made as outlined in IEEE Std 118-1978 [7]. The average temperature of the winding should be recorded at the time the cold resistance is measured. The temperature of the surrounding air shall not be regarded as the temperature of the windings, unless the machine has been standing idle under constant temperature conditions for a considerable period of time. Extreme care should be taken to secure accurate cold resistance measurements since a small error in measuring resistance will cause a comparatively large error in determining the temperature.

4.2.1 Temperature Correction of Winding Resistances. The equation to be used to correct the measured cold resistance to a common temperature standard such as 25 °C is:

$$R_1 = R_2 \frac{(k + t_1)}{(k + t_2)}$$

where

R_1 = resistance of winding (ohms) measured at cold temperature standard t_1 (°C)

R_2 = resistance of winding (ohms) measured at temperature t_2 (°C)

k = 234.5 for copper

= 225 for aluminum (EC grade based on a volume conductivity of 62%)

4.2.2 Method of Resistance Measurement. The bridge method is the preferred method. The voltage-drop method may be used as an alternate method.

4.2.2.1 Shunt-Field-Circuit Windings. The cold resistance of the shunt field shall be determined at the terminals of the shunt field with proper connections excluding all external resistances.

4.2.2.2 Armature-Circuit-Winding Resistances. The armature-circuit-winding resistance comprises the sum of the various components (excluding brush and brush-contact resistance) connected in accordance with the winding diagram of the machine. This summation should be made only after each resistance component has been corrected to a common temperature. These components are measured as indicated below:

(1) *Armature Winding*

(a) *Method A.* This method is limited to wave-wound armatures including all two-pole rotor windings. For other winding types, or if the winding type is not known, Methods B or C given below should be used.

Using this method, the armature resistance can be determined by applying a resistance bridge across two commutator segments as near as possible to one pole pitch apart. In the case of simplex, two-pole rotor windings having an odd number of segments, one bridge contact should cover two adjacent segments. In the case of duplex windings, each bridge contact shall cover two adjacent segments.

(b) *Method B (Preferred).* A suitable low-resistance harness should be connected to the rotor winding either at the risers or end clips or on the commutator segments so as to contact the rotor winding at each brush location. For a simplex winding the harness should contact one commutator segment per pole spaced one pole pitch apart. In the case of nonintegral spacing, the contact may be made to two adjacent commutator segments simultaneously. For a duplex rotor winding the harness should contact two adjacent commutator segments simultaneously at each brush position. In case the rotor winding type is not known, a close approximation to the winding resistance may be attained by connecting the harness as described for a duplex winding or Method C may be applied.

The resistance measured by connecting the bridge between the terminal legs of this harness simulating the positive and negative brushes is considered as the rotor winding resistance. Care shall be taken to reduce the contact resistance to a negligibly low value.

(c) *Method C (Alternate).* This is the voltage-drop method of measuring the armature resistance. The brush rigging should be properly assembled. The brush fit should be good (see 4.6.1). The rotor should be suitably blocked to prevent rotation. The brush rigging should be used as the current connection and the potential drop measured as follows: The two potential leads should be applied to the commutator segments approximately one pole pitch apart. These leads should be located on segments as near the center of the brush contact surface as possible. The potential leads should be shifted and readings recorded for each pole pitch. The current shall be maintained constant for all of these measurements. The current should not exceed 10% of the rated value. The resistances shall be computed from the average of all of the potential-drop readings and the circulating current. Usually this will give a lower value of resistance than the value measured using Methods A or B.

CAUTION: *The current and the time it is applied shall be limited to prevent damage to the commutator due to local heating from this circulating current.*

(2) *Commutating-Field Winding.* On uncompensated machines, the resistance of this winding may be measured directly at its terminals. If one end of the winding is permanently connected to the brush rigging, the commutating field resistance should be measured between this point and the outside terminal. On machines that are compensated, this winding may be interleaved with the compensating-field winding (pole-face winding). In such designs the combined resistance of these two windings should be measured.

If the windings are split and located electrically on opposite sides of the armature or arranged in some other manner, the resistance of each winding component should be measured individually.

(3) *Compensating-Field Windings.* If separate from commutating-field windings, the resistance should be measured at the terminals of this winding.

(4) *Series-Field Windings.* The resistance should be measured at the terminals of all distinct windings. If the winding is permanently connected to one of the other stationary windings and with only one distinct connection strap between the two windings, the series-field resistance should be measured between the terminal and this distinct connection strap. If the series-field winding is interleaved, or does not have a distinct connection between windings, then its resistance should be measured in combination with the other stator windings to which it is interconnected.

(5) *Shunts.* The resistance of any shunts connected in parallel with the machine windings should be measured at the cable terminals of the shunt. The shunts shall be disconnected from the windings when measuring the winding and shunt resistances. The windings shunted by these various resistors should be identified with the resistance of the shunts.

(6) *Auxiliary Windings and Associated Series Resistors.* The resistance of all auxiliary windings should be measured at the terminals. The resistance of all auxiliary winding adjusting resistors should be measured at the terminals of the cables which join these resistors to the winding. In addition to the resistance, the connections of all adjusting resistors should be recorded.

4.3 Air Gap Measurements. The measurement of the air gaps should include a check of correct installation of main poles, test of possible deformation of bearing or bearing support, inspection for sufficient clearance before testing, and proper assembly of rotor with respect to stator. Dissymmetry in main- or commutating-field pole air gaps may cause difficulties such as excessive voltage ripple or overheating of equalizers.

Measure the minimum air gap beneath the center (approximately) of each main pole and each commutating-field pole piece using a suitable feeler gage or tapered gage to determine the gap to at least the nearest 0.100 mm (0.005 in) for integral-horsepower motors and to the nearest 0.050 mm (0.002 in) for fractional-horsepower motors. All measurements should be made between iron surfaces of the pole pieces and the rotor. In normal practice, a common point on the rotor is selected and the point is rotated to each pole in turn as measurements are made.

Where apertures are not provided, the uniformity of the air gap can be determined by ascertaining that the rotor turns freely in the assembled machine when wound with a wire spaced spirally around the rotor periphery. For this test the diameter of the wire should be at least 70% of half the difference between the diametric distance of the main pole faces and the outside diameter of the rotor.

4.3.1 Data Record. This procedure recommends uniformity in pole identification. Main pole No 1 and commutating-field pole No 1 shall be either the top pole or the first pole of each kind in a clockwise direction from the vertical centerline above the horizontal centerline when the machine is viewed from the commutator end. Each main pole will be numbered starting with pole No 1 and proceeding consecutively in a clockwise direction.

For a machine with a vertical shaft, the No 1 pole is the first one in a clockwise direction as viewed from the commutator end of the machine from some designated point such as the nameplate or direction of rotation mark. This point should be identified on data record.

4.4 Polarity and Impedance Drop of Field Coils.

4.4.1 Polarity. The polarity of the various field windings may be determined by any of the methods indicated below. Each field-winding polarity should be ascertained independently.

Polarity may be checked by means of a compass while passing current through all of one type of field coils connected in series or by observing the attraction or repulsion between the ends of two short, soft-iron bars bridging between adjacent pole tips.

Field coils that are constructed of large size conductors that may be easily traced throughout the winding may have their polarity checked by tracing the winding and applying the right-hand rule.

4.4.2 Impedance Drop. Since a dc resistance test is apt to be insensitive to the detection of variations among the field coils, an ac impedance drop test is recommended. A coil having shorted turns will be indicated by a low impedance when compared to that of the other coils.

4.5 Vibration. Motor vibration caused by mechanical or electromagnetic dissymmetry should be measured using a low ripple source of direct current such as a generator. Such measurements are usually made at no load and at rated speed using a half-key in the shaft extension. The frequency of vibration is related to the speed of rotation.

On rectified power, in addition to vibration caused by mechanical or electromagnetic dissymmetry, vibrations may be experienced related to the amplitude and frequency of the ripple components of armature and field current. The power supply used should be in accordance with 3.5.2. Tests should be conducted at various loads over the entire speed range of the machine including speed control by armature voltage where applicable. To differentiate between vibration due to current ripple and that due to slot ripple or other factors, the vibration frequencies should be examined as the speed of rotation is changed slowly. Natural frequencies of machine mechanical parts may be excited by power supply frequencies, harmonics, or sub-harmonics acting independently or reinforced by slot ripple. Also, measurements can be made with varying degrees of current ripple as accomplished by the use of a smoothing reactor or by using a low ripple power supply, such as a dc generator. Vibration velocity is the recommended measurement quantity.

Radially- and axially-directed vibration measurements should be made at the machine bearing housing. If the bearing housings are not accessible the readings should be taken at the housing support as near the housing as possible.

Mounting conditions will affect the vibration of the machine. Machines provided with self-supporting bases, or of the end-shield type construction, may be mounted in such a manner as to make them independent of mounting conditions. On large machines this becomes impractical and experience has shown it to be unnecessary. To obtain measurements that are as nearly as possible independent from mounting conditions, the machine should be placed on flexible pads or springs. These should compress by the weight of the machine alone, in amounts not less than the values shown below.

Speed (r/min)	Minimum Compression (mm)	(in)
7200	0.4	$\frac{1}{64}$
3600	1.5	$\frac{1}{16}$
1800	6	$\frac{1}{4}$
1200	15	$\frac{9}{16}$
900	25	1
720	40	$1\frac{9}{16}$
600	55	$2\frac{1}{4}$

The value for minimum compression at other speeds may be determined from the equation:

$$c = \left(\frac{k}{v}\right)^2$$

where

k = 4500 for c (millimeters)
900 for c (inches)
v = speed (r/min)

The pads or springs should be selected so that the compression is not more than one-half of the unloaded thickness.

4.6 Brush Setting. The best brush position for good commutation and the desired voltage or speed characteristics of generators or motors, respectively, shall be determined by observation of the machines under load. The manufacturer of direct-current machines determines the brush position which gives successful commutation and provides reference marks and directions which permit this position to be relocated. On some machines, the brush rigging is fixed and cannot be moved. When provision is made for moving the brush rigging, one of the methods in 4.6.2, 4.6.3, and 4.6.4 may be used to determine the electrical neutral.

4.6.1 Definition—good brush fit. At least 75% of the brush face area and 100% of the circumferential brush arc are in apparent contact with the commutator.

4.6.2 Reverse Rotation Method (Full-Load Neutral). Reversible machines may have the neutral located by this method. Operate the machine at constant voltage, constant field current, and constant armature current. The fit between brush face and commutator shall be good. Measure the rotational speed for both directions of rotation. When the brushes are located on neutral, the rotational speed should be nearly the same in both directions. The machine should be run at near rated load and near top operating speed. To avoid speed inconsistencies caused by magnetic hysteresis in the direct and quadrature axes, the field current should be adjusted in the same manner in the tests in both directions of rotation. Also, excessive armature current should not be allowed to flow, particularly during acceleration and stopping.

4.6.3 Moving Armature Through Small Angle (Kick Method). The no-load or inductive neutral may be located by observing the voltage induced in the stationary armature winding by alternately establishing and destroying a flux in the main poles. The usual procedure is as follows: Raise the brushes. Select two commutator segments spaced one pole pitch apart (total segments divided by number of poles). In case the bars per pole pitch is not an integral number, two sets of readings should be taken; one with a pitch of the next integral number below full pitch and one with the next higher number. A weighted average between the two will represent the readings sought. Connect to these segments a low-reading direct-potential voltmeter or millivoltmeter. Employ a quick-break auxiliary-jaw knife switch to ensure a more uniform rate of interruption of current. Arrange to excite the main field from a separate direct-current source with not more than 20% of normal current which may be established and interrupted by means of the quick-break switch.

On opening the switch, the decaying field flux will induce a voltage in the armature coils between the selected segments and this kick will be read on the voltmeter. Observe the direction of the induced voltage upon removal of the field.

The armature should be turned a few degrees at a time, with the voltmeter always connected to the same segments and the observation repeated until a position is found so that interrupting the field current produces a minimum indication on the voltmeter. When this occurs, the portion of the winding between the voltmeter leads is equally or symmetrically located under the poles and the center of the brush faces should be set on these points.

NOTE: A low-reading voltmeter or millivoltmeter should be used to ensure a discrete null-point location.

4.6.4 Armature Stationary (Kick Method)

4.6.4.1 Measurement with Brushes Raised. If the armature cannot be rotated readily, for example on large machines or multiple units, the voltmeter leads may be moved around the commutator maintaining one pole pitch between leads.

The neutral point on the commutator is then at the two segments where the minimum voltmeter indication is obtained when the field current is switched, see 4.6.3. The centers of the brushes should be set on these points. In cases where the bars per pole pitch is not an integral number, the voltmeter leads shall still remain a pole pitch apart and a number of readings should be taken on either side of the point where the kick reverses. The point at which a curve plotted from these readings passes through zero will indicate the no-load neutral position.

4.6.4.2 Measurement with Brushes Down. This method is similar to that of 4.6.4.1 except that the inductive voltage is measured through the brushes. All the brushes may be down, though some may be lifted in case the brush friction tends to also rotate the armature as the brushes are shifted. The brushes shall have a good fit. Connect a low-reading millivoltmeter to two adjacent brush arms.

First, loosen the brush rigging so it can move freely. Next, move the brush rigging from the assumed mechanical neutral position approximately two commutator segments in the direction of machine rotation. From this position, move the brush rigging in small increments back against the direction of machine rotation; at each position, make and break the field current and record the meter deflection and direction of deflection for both make and break condition. A zero-center millivoltmeter or a recorder should be used for this purpose. Continue to move the brush rigging approximately two commutator segments past the electrical neutral position.

Plot on graph paper the meter readings as a function of the brush position and draw a straight line through each set of points; the two lines, one for making and one for breaking the field current, will intersect on or near the abscissa; this is the neutral brush position to which the brushes should be moved.

Reversing machines should have the neutral position identified by moving the brush rigging first in one direction, then in the opposite direction; for each direction, a set of meter readings should be taken as indicated above. The final neutral position is the average value of the two curve intersections as plotted above.

4.7 Insulation Resistance. The resistance of the insulation between the windings and frame is rarely measured on small or low-voltage machines, but is commonly taken on large (200 hp and larger) and higher voltage (250 V and above) machines, and on machines subjected to insulation damage from exposure or severe service.

The insulation resistance to ground is a useful indication of whether or not the machine is in suitable condition for the application of a high-potential test or running tests. In those cases where insulation resistances are being recorded, it is important to obtain a good set of initial values for future comparative purposes.

For test methods see ANSI/IEEE Std 43-1974 [3].

4.8 High-Potential Tests. In the interests of safety, precautions should be taken to prevent anyone coming in contact with any part of the circuit or apparatus while dielectric tests are in progress.

WARNING: *Due to the high voltage used which could cause permanent injury or death, high-potential tests should be conducted only by experienced personnel, and adequate safety precautions should be taken to avoid injury to personnel and damage to property.*

This test should be applied when, and only when, the machine is in good condition and the insulation resistance is not impaired due to dirt or moisture. Tested windings should be discharged carefully to avoid injury to personnel on contact.

4.8.1 The high-potential test voltage should be successively applied between each electric circuit and the frame (or the core in case of rotor). The windings not under test and all other metal parts should be connected to the frame (or core) during this test. The frame (or core) should be suitably grounded during this test. All accessories such as capacitors, reactors, autotransformers, etc which may be damaged by high voltage should be disconnected during this test. The accessories should be subjected to the high-potential test applicable to the class of apparatus to which the accessory belongs. Such tests should be made at the point of their manufacture.

The value of high-potential test voltage and its frequency, wave shape, duration, and crest value shall be in accordance with ANSI/NEMA MGI-1978 [5], Sections 3.01, 12.03, 15.48, 23.50, or 24.48 as applicable.

CAUTION: *Repeated application of the high-potential test degrades the dielectric qualities of the insulation system.*

4.8.2 No leads should be left unconnected during the test as this may cause an extremely severe stress at some location in the winding. In making the test, the voltage should be increased smoothly to full value as rapidly as is consistent with its value correctly indicated by the meter. After the specified duration of the test voltage, it should then be reduced at a rate that will bring it to one-quarter value or less in not more than 15 s.

CAUTION: *The voltage should never be switched off from full value in one step.*

For measurement of high potential test voltage, see ANSI/IEEE Std 4-1978 [2]. The transformer-voltmeter method of measurement is commonly used.

5. Performance Determination

5.1 Magnetic Saturation. The no-load saturation curve is a nonlinear relationship between the armature terminal voltage and field current at rated base speed and zero armature current. The data should be taken at properly spaced voltages to permit an accurate plot from zero field current up to approximately 125% of rated voltage.

5.1.1 Separately Driven. The machine should be driven at rated speed by any suitable means. If possible, field current should be supplied from a separate source to stabilize the voltage and facilitate the taking of data. Simultaneous readings of field current, armature voltage, and speed should be taken.

> **CAUTION:** *If the machine being tested has no commutating poles and is constructed with brushes located off neutral such a test may be damaging and lacking in significance.*

5.1.1.1 Ascending Curve. A set of readings should be taken beginning with zero field current and increasing until maximum voltage is obtained. Three of the readings taken should be as near as possible to 90%, 100%, and 110% of rated voltage.

To avoid inconsistencies caused by hysteresis effects, the armature terminal voltage should never be carried above the intended test point and then decreased. If this should occur during the test, the field current should be reduced to zero and the armature terminal voltage increased to the intended test point.

5.1.1.2 Descending Curve. Another set of readings may be obtained by starting at maximum armature terminal voltage and decreasing field current to zero. To avoid inconsistencies caused by hysteresis effects, the armature terminal voltage should never be carried below the intended test point and then increased. If this should occur during the test, the field current should be increased to the maximum value and the armature terminal voltage decreased to the intended test point.

5.1.2 Self-Driven (Except Series-Wound Motors). If no suitable separate drive is available, data for an approximate no-load saturation curve may be taken by operating the machine as an uncoupled motor from a separate source of ripple-free direct-current power. This source must be adjustable from approximately 25% to 125% of rated voltage. The effects of magnetic hysteresis should be avoided as discussed in 5.1.1.1 and 5.1.1.2. Field current required to obtain rated speed at the different voltages differ from no-load saturation data because of the effects of the armature current which is required to operate the machine as an uncoupled motor. The machine may become unstable at low voltage and precautions against overspeed should be observed.

5.2 Commutation. Successful machine commutation is attained if neither the brushes nor the commutator are burned or injured in the conformance test or in normal service to the extent that abnormal maintenance is required. The presence of some visible sparking is not necessarily evidence of unsuccessful commutation.

On rectified power, motor commutation will be affected by the ac line reactance, dc line reactors or impedances, and the relationship of the ac voltage to the dc voltage. It is important, therefore, when judging commutation to use a power supply having characteristics which are as similar as possible to the intended power supply. See also 3.5. The apparent visible commutation will generally seem more severe on rectified power supply. Because of the persistence of the eye, very short sparking appears as prolonged or continuous sparking. Commutation shall be observed over a long period of time to accurately evaluate whether harmful sparking is occurring.

5.3 Regulation. (Not applicable to series-wound motors)

5.3.1 Speed Regulation of Motors. The purpose of this test is to determine the variation in motor speed as the load is decreased uniformly from rated load to no-load with constant armature voltage and constant field current. The test procedure is as follows:

5.3.1.1 This test should be taken after the motor has attained a stabilized temperature resulting from continuous operation at rated load. Test points should be taken rapidly so that the temperature of the windings does not change appreciably. Operate the motor maintaining rated armature voltage and rated field current. If the motor uses a field rheostat in service, adjust the rheostat to obtain rated speed at rated armature current and voltage.

5.3.1.2 Gradually remove and apply full load several times until consistent readings are obtained. Record the respective full-load and no-load speeds and calculate the speed regulation in accordance with the following equation:

$$\text{Percent speed regulation} = 100\left[\frac{\begin{pmatrix}\text{speed at}\\ \text{no-load}\end{pmatrix} - \begin{pmatrix}\text{speed at}\\ \text{rated load}\end{pmatrix}}{\text{speed at rated load}}\right]$$

When requested, more complete speed-load test data can be taken.

5.3.2 Voltage Regulation of Generators. The purpose of this test is to determine the change in terminal voltage which accompanies the gradual removal of rated armature current with the main field adjustment for rated load voltage undisturbed. The test procedure is as follows:

5.3.2.1 If the generator is self-excited, the rheostat setting should remain fixed during the test load changes. If the generator is separately excited, the rated-load field current should be maintained during the tests.

The generator should be operated at rated speed. The test should be taken after the generator has attained a stabilized temperature resulting from continuous operation at rated speed and load. Test points should be taken rapidly enough that the temperature of the windings does not change appreciably.

5.3.2.2 Gradually remove and apply rated load several times until consistent readings are obtained. Record the respective full-load and no-load voltages and calculate the voltage regulations in accordance with the following equation:

$$\text{Percent voltage regulation} = 100\left[\frac{\begin{pmatrix}\text{voltage at}\\ \text{no-load}\end{pmatrix} - \begin{pmatrix}\text{voltage at}\\ \text{rated load}\end{pmatrix}}{\text{voltage at rated load}}\right]$$

When requested, a more complete voltage-load test can be taken.

5.3.3 Combined Voltage Regulation of Generator and Prime Mover. The test procedure given in 5.3.2.2 is for the inherent voltage regulation. The combined voltage regulation is taken by the same procedure except the speed-load characteristic of the generator's prime mover is introduced. The generator should be driven at rated speed at rated load. The speed at all other points should be from the inherent speed-load characteristics of the generator's prime mover. If the exact speed-load characteristic is unknown, it should be assumed to be a straight-line function throughout the load range.

5.4 Efficiency. Efficiency is the ratio of output power to total input power. Output power is equal to input power minus the losses. Therefore, if two of the three variables (output, input, losses) are known, the efficiency can be determined by one of the following equations:

$$\text{Efficiency} = \frac{\text{output power}}{\text{input power}}$$

$$\text{Efficiency} = \frac{\text{input power} - \text{losses}}{\text{input power}}$$

(Particularly applicable to motors)

$$\text{Efficiency} = \frac{\text{output power}}{\text{output power} + \text{losses}}$$

(Particularly applicable to generators)

For motors, input power can be determined by measuring the armature circuit and shunt-field power including the dc and ac components if operation is on rectifier power, as described in 3.4. Output power can be determined by measuring the mechanical output using a torquemeter or dynamometer and a tachometer as described in 5.4.3.1 and 5.4.3.2. The segregated losses can be determined as described in 5.4.5 and 5.5.

For generators, input power can be determined as the sum of the mechanical power input, measured using a torquemeter or dynamometer and a tachometer, and the electrical power input to the shunt field. Output power can be determined as the product of the measured armature terminal voltage and current. The losses can be determined as described in 5.4.5 and 5.5.

5.4.1 Reference Conditions

5.4.1.1 Unless otherwise specified, efficiency data shall be determined for the rated voltage and speed. In the case of adjustable speed motors, the base speed shall be used unless otherwise specified.

5.4.1.2 In determining individual I^2R losses for efficiency calculations, the resistances of the windings shall be corrected to a temperature equal to an ambient of 25°C plus the observed rated-load temperature rises by resistance. When the rated-load temperature rises have not been measured, refer to ANSI/NEMA MG1-1978 [5], for the temperature to be used in correcting winding resistances.

5.4.1.3 If input-output tests are used for determining efficiency, they should be made as nearly as possible at the final temperature attained at operation for the time specified in the rating under the conditions above.

5.4.1.4 Losses other than I^2R losses are not to be corrected for temperature if data are taken under standard conditions. See 4.1.2.

5.4.2 Methods. In general, for the size of machines indicated, the following methods should be used for which the precautions listed in Section 3 of these procedures shall be observed:

Machine Size	Machine Method
Fractional horsepower	Brake, dynamometer, or torquemeter
Integral horsepower	Dynamometer, torquemeter, brake, pumpback or segregated loss

5.4.3 Direct Measurements of Input and Output. Direct measurements of input and output are always made on fractional-horsepower machines and generally on small machines but they become increasingly more difficult as the size of the machine increases because of limitations of available test equipment.

Readings. Readings of current and voltage input (or output), speed and torque output (or input), ambient temperature, armature temperature or resistance, and field coil temperatures or resistances, should be obtained for six load points substantially equally spaced from 0.25 to 1.5 times rated load. With series excited motors, the minimum load is determined by the speed limitations of the machine. For readings to be used in performance determinations, the machine temperature rise shall be some value between 50% and 100% of rated temperature rise.

On rectified power, (See Form C) the following readings should be taken at each of the six load points:

Reading	RMS Value	Average Value
Voltage input to power supply, all phases	X	–
Voltage input to armature circuit	*	X
Current input to armature circuit	*	X
AC component of armature-circuit current	X	–
Power input to armature circuit	–	*
AC component of power input to armature circuit	–	X
Voltage input to shunt-field circuit	*	X
Current input to shunt-field circuit	*	X
Power input to shunt-field circuit	–	*
Speed	–	X
Torque	–	X
Armature temperature or resistance	–	X
Field-coil temperatures or resistances	–	X
Ambient temperature	–	X

*Optional

5.4.3.1 Brake Method. Care should be exercised in the construction and use of the brake and brake pulley. The tare shall be carefully determined and compensation provided. Performance of a motor shall be calculated as shown in Form D.

5.4.3.2 Dynamometer or Torquemeter Method. When the dynamometer or torquemeter method is used, the shaft power is obtained from the following equation:

$$P = \frac{T \cdot n}{k}$$

where

P = shaft power (kilowatts)
T = torque
n = rotational speed (r/min)
k = constant related to units used

T	k
newton meters	$9.549 \cdot 10^3$
pound-force (ft)	$7.043 \cdot 10^3$
ounce-force (in)	$1.352 \cdot 10^6$

To obtain accurate results, the dynamometer rating should not exceed three times the test machine rating and it should be sensitive to a torque of 0.25% of its rated torque. Dynamometer correction should be made as outlined in Form D.

The cradle bearing friction in the dynamometer may result in scale readings differing, for the same value of electric power, depending upon whether the load is increasing or decreasing prior to reading. Accordingly, the average of two sets of readings should be taken. The first set should be taken while gradually increasing the load; the second set while decreasing the load. Care should be taken in each case not to overrun the points to be read. Curves of torque versus electric power should be plotted for each set of readings and the average of the curves shall be used.

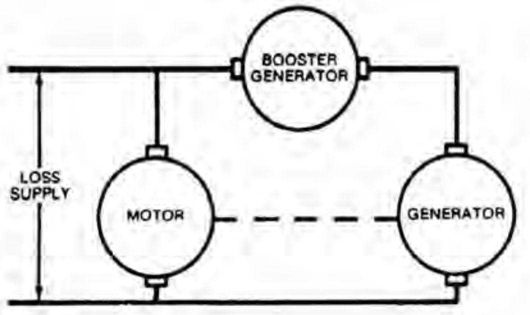
In special cases during the testing of a motor, it may be desirable to make a check test, operating the machine as a generator and the dynamometer as a driving motor. The test is made in exactly the same way as for the usual motor input-output test, but in this case the total loss will be equal to the mechanical input minus the electrical output instead of being equal to the electrical input minus the mechanical output.

Any errors in any of the scales or meters will occur in opposite directions in the two tests, and the average of the stray-load losses given by the two tests will, therefore, be nearly correct even though relatively large errors have occurred in the calibrations.

It is recommended that the test operating the machine as a generator be made at rated speed and voltage, and with the same mechanical torque on the dynamometer as in the test of the machine as a motor. The stray-load losses found in the generator and motor tests should be separately determined in each case by subtracting from the measured total loss the armature circuit I^2R loss at the temperature of test, the core loss and friction and windage. Judgment should be exercised in interpreting the stray load loss so obtained, as the temperatures of the windings may not be known accurately. Furthermore, large errors may occur when two large numbers are subtracted from one another. Several load points should be taken for each test and the resulting stray-load losses plotted against armature current. A single curve drawn through the averages of the motor and generator test results gives the final stray-load loss value. Adding this to the other losses gives the total losses and hence the efficiency. Form E may be used for this calculation.

5.4.4 **Pump-Back Method.** This method may be used when duplicate machines are available. The two machines are coupled together and electrically connected as shown in Fig 1. One machine is operated as a motor and the other as a generator. The main power is pumped-back and only the losses are supplied. Approximately, the *booster generator* supplies the load loss and the *loss supply* supplies the no-load loss. This test can be taken omitting the booster generator; however, system instability may be encountered.

Fig 1
Schematic Connection Diagram for Pump-Back Test



5.4.4.1 The motor and generator should be operated with the field strength required to produce the calculated internal voltage corresponding to the load tested.

5.4.4.2 The total loss in the two machines equals the power supplied by the *loss supply* and *booster generator* plus losses in any separately excited fields that are used, minus the losses in the cables, bus bars, switches, breakers, etc, used to connect the machines.

5.4.4.3 Tests should be conducted at six load points and readings should be taken as indicated in 5.4.3. The machine efficiency shall be determined as outlined in Form F.

5.4.5 **Segregated Loss Method.** When the motor efficiency is determined by the segregated loss method, the following losses shall be used:

Type of Loss	Description of Test or Calculation
Armature I^2R	5.5.1
Series connected windings I^2R	5.5.2
Brush contact	5.5.3
Stray load	5.5.4
Shunt field I^2R	5.5.5
Rheostat	5.5.6
Exciter	5.5.7
Rotational core	5.5.8
Brush friction	5.5.9
Friction and windage	5.5.10
Ventilating	5.5.11

5.5 Description of Losses

5.5.1 **Armature I^2R Loss.** The armature I^2R loss is the square of the armature current at the load being considered, multiplied by the armature resistance as measured using direct current and corrected to the proper reference temperature. See 5.4.1.2.

On rectified power, the armature I^2R loss shall be calculated as the product of the square of the rms value of the current and the temperature-corrected dc resistance of the armature winding.

5.5.2 **Series-Connected Windings I^2R Loss.** Series windings (includes interpole or compensating windings when used) I^2R loss is the product of the current in the series-connected field windings squared, and the measured resistance corrected to the proper reference temperature. See 5.4.1.2. In case shunts or auxiliary field, windings are used across any of these fields, the multiple resistance should be used.

On rectified power the I^2R loss of the series-connected windings shall be calculated as the product of the square of the rms value of the current and the temperature-corrected dc resistance of the winding.

5.5.3 Brush-Contact Loss. The brush-contact loss may be determined by the product of the armature current and a voltage drop. The total voltage drop (that is, for both polarities) that shall be used in determining this loss is as follows:

Carbon, electrographitic, and graphite brushes, shunts attached	2.0 V
Carbon, electrographitic, and graphite brushes without shunts	3.0 V
Metal-graphite brushes, shunts attached	0.5 V

This voltage drop shall be assumed to be the same value for all loads.

On rectified power, the brush-contact loss shall be calculated as the product of the brush-contact voltage and the rms value of the armature current.

5.5.4 Stray-Load Loss. Stray-load loss is the additional loss in the machine due to load that is not included in any of the other loss categories in 5.5. These losses are of two types:

(1) Stray-load losses resulting from the dc component of the armature current

(2) On rectified power, additional stray-load losses resulting from rectifier operation

5.5.4.1 In the absence of test measurements, the dc stray-load loss component shall be taken as 1% of the output power. Two methods of determining the dc component of the stray-load loss are given in 5.5.4.2 and 5.5.4.3 if needed.

5.5.4.2 The dc component of the stray-load loss may be determined from the dynamometer test, 5.4.3.2. Form E may be used to calculate stray-load loss.

5.5.4.3 The dc component of the stray-load loss may be determined from the pump-back test, 5.4.4, by subtracting all of the other applicable losses from the total loss supplied to the machines tested. Form G may be used to calculate stray-load loss.

5.5.4.4 On rectified power, and for shunt-wound motors, the additional stray-load loss can be measured by subtracting the ac component I^2R losses in the armature circuit windings from the ac component of the power input to the armature circuit. For measurement of the ac components of the armature current and of the armature circuit power input, see 3.4.1.

For series-wound motors, a small amount of the ac power input contributes to the developed motor torque. This amount is usually so small that it can be neglected.

5.5.5 Shunt-Field I^2R Loss. The shunt-field I^2R loss is the product of the field current squared and the measured resistance of the field windings, corrected to the proper reference temperature. See 5.4.1.2. The field current is the current required by the field for the load at which the loss is computed.

On rectified power, the shunt field I^2R loss should be calculated in accordance with 3.4.2.

5.5.6 Rheostat Loss. Usually, all losses due to field rheostats are not included in determining machine efficiency. If this loss is to be included, it may be computed by taking the product of the excitation system voltage and the field current for the load at which the loss is computed and subtracting the shunt-field I^2R loss.

On rectified power, the rheostat loss should be calculated using the rms value of the current; however, the average value can be used if the shunt-field current is essentially ripple-free as defined in 1.1.

5.5.7 Exciter Loss. Usually, the losses of all exciters are not included in determining machine efficiency.

5.5.8 Rotational Core Loss. The rotational core loss shall be taken as the difference in power required to drive the machine at given speed when excited to produce an open-circuit voltage at the terminals corresponding to the calculated internal voltage and the power required to drive the unexcited machine at the same speed. The internal voltage shall be determined by correcting the rated terminal voltage for the armature circuit resistance drop including the contact drop of the brushes of both polarities as specified in 5.5.3 and using the equations given in 5.6.1.1. Detailed measurement instructions are given in 5.6.

CAUTION: *If the machine being tested has no commutating poles and is constructed with brushes located off neutral, such a test may be damaging and lacking in significance.*

5.5.9 Brush-Friction Loss. Experience has shown that wide variations are obtained in tests of brush friction made at the factory before the commutator and brushes have developed the smooth surfaces that come after continued operation. Conventional values of brush friction, representing average values of many tests, shall therefore be used as follows:

$$F = k \cdot v \cdot a$$

where

F = brush friction (watts)
v = surface velocity
a = brush contact area
k = constant related to the brush type and units of variables used as tabulated below:

Brush Type	Velocity Units	Area Units	k
Carbon, Electrographitic, Graphite	m/min	mm^2	$4.0 \cdot 10^{-5}$
	ft/min	in^2	$8.0 \cdot 10^{-3}$
Metal graphite	m/min	mm^2	$2.5 \cdot 10^{-5}$
	ft/min	in^2	$5.0 \cdot 10^{-3}$

In the event that the conventional values in 5.5.9 are questioned, the brush friction can be measured by taking the difference between the power required to drive the machine with brushes in place and with brushes raised observing the precautions given in 5.6.1.4.

5.5.10 Friction and Windage Loss. The friction and windage loss, excluding brush friction, is the power required to drive the unexcited machine at rated speed with its brushes lifted.

5.5.10.1 In the case of a machine furnished with incomplete bearings, the friction and windage loss should usually not be included in determining machine efficiency. The friction and windage loss may be supplied separately from the efficiency if this information is requested.

5.5.10.2 The additional losses due to direct-connected flywheels, or other direct-connected apparatus, should usually not be included in determining machine efficiency.

5.5.11 Ventilating Losses. The power required to circulate the gas through the machine and ventilating system if one is provided, whether by self-contained or external fans, shall be charged against the machine except as specified below.

5.5.11.1 The power required to force the gas through parts of the ventilating system external to the machine and cooler should usually not be included in determining machine efficiency.

The power required for air ventilation may be conveniently found by using the following equation:

$$P = \frac{k \cdot \text{(pressure drop)} \cdot \text{(volume rate of flow)}}{\text{per unit blower efficiency}}$$

where
P = input power (watts)
k = constant related to units used as follows:

Pressure Units	Flow Units	k
Pa (N/m^2)	m^3/s	1.0
millimeters of water	L/min	0.0163
inches of water	ft^3min	0.117

5.5.11.2 In those cases in which an external fan is employed to supplement the fanning effect incorporated in the structure of the machine for the purpose of compensating for pressure drops in long or restricted ducts, the power input of the external fan should usually not be included in determining machine efficiency.

5.5.11.3 Ventilating-Loss Tests. Machines may be tested at the factory without cooler and external duct system, but with the fan running as in service, and the losses so measured should be used in calculating the efficiency of the machine. This practice is permissible because, in most practical cases, the difference between the ventilation losses with free entrance and discharge, and the ventilation losses with normally restricted entrance or discharge, or both, will be relatively small.

In general, this test procedure will be followed where the losses in the external ducts and cooling system are relatively small compared with the losses in the machine.

5.6 Measurement of Rotational Losses. In general, the individual losses, except the I^2R, brush contact, brush friction, and stray-load losses, are determined from calculations of measurements of the power input required to run the machine under specified conditions using the mechanical input method, the electrical input method, or by using the retardation method.

5.6.1 Mechanical Input Method. The mechanical input method consists of driving the test machine at no-load with a dynamometer or with a suitably calibrated motor. When the machine is excited in accordance with 5.6.1.2, the output of the dynamometer or driving motor is the power required to supply the rotational losses of the machine under the condition of test.

5.6.1.1 All brushes should be raised except those required for the measurement of armature voltage. With the test machine driven at no-load at rated speed, the main field winding should be separately excited so that the armature terminal voltage is equal to the internal voltage developed by the machine in service at rating as explained below.

The internal voltage in a motor is lower than the voltage impressed on the armature circuit while the internal voltage in a generator is higher than the terminal voltage by an amount equal to the resistance drop of the armature and series-connected field windings at rated-load, and the sum of the contact drop of the brushes of both polarities:

For motors: $E = V - IR_a - V_b$

For generators: $E = V + IR_a + V_b$

where

E = internal voltage at rating (volts)
V = rated armature circuit voltage (volts)
I = rated armature current (amperes)
R_a = temperature-corrected resistance of armature and series-connected field windings (commutating, compensating, and series) as used in service (ohms) (see 5.4.1.2)
V_b = brush-contact drop (volts) (see 5.5.3)

5.6.1.2 The machine should be operated at rated speed, preferably at rated load, for several hours so as to stabilize friction factors. During this warm-up period, it is necessary that all brushes be in place on the commutator. Following this warm-up period, raise all brushes except two (one of each polarity) and measure the mechanical power input carefully with the machine running at no-load at rated speed and with the field excited in accordance with 5.6.1.1. The rotational losses so measured consists of the sum of the rotational core loss and the friction and windage loss including brush friction with the brushes used.

5.6.1.3 The rotational core loss can be evaluated by observing the decrease in mechanical power input as the field excitation voltage is decreased to zero.

5.6.1.4 The brush friction loss under the condition of test can be evaluated by removing the field excitation and observing the difference between the power required to drive the machine with brushes in place and with brushes raised. If it is desired to measure brush friction representative of the test machine in service, a test should be taken with all brushes assembled at the prescribed brush pressure. Surfaces of the commutator and brushes should be smooth and polished from running following several hours of operation at rated speed and load. It should be recognized that brush friction varies widely with load current and with temperature so that the losses derived from measurements at no-load can differ widely from the amount of brush friction encountered in service.

5.6.2 Electrical Input Method. Using this method, the rotational losses are determined from measurements of the power required to operate the test machine as a motor at no-load at rated speed and with field excitation adjusted so as to generate an internal voltage equal to the value developed by the machine in service at rating. A rectifier power supply should not be used.

5.6.2.1 Excite the main field winding at rated value and operate the machine as a motor at rated speed, preferably at rated load, for several hours so as to stabilize friction factors. It is necessary that all brushes be in place during this period.

5.6.2.2 Stop the machine, uncouple it from the loading means, and raise all of the brushes except two (one of each polarity). Measure the resistance of the armature and series-connected field windings. Restart the machine and, running as a motor at no-load and at rated speed, adjust the main field excitation and armature circuit voltage so that the internal voltage is equal to the value developed by the machine in service at rating, as determined using the appropriate equation given in 5.6.1.1. The internal voltage at test is determined using the first of these equations except using R_a equal to the measured resistance of the armature and series-connected field windings.

5.6.2.3 With the machine uncoupled and with the speed and field excitation adjusted in accordance with 5.6.2.2, carefully measure the power input to the armature circuit. This power is the sum of the rotational core loss, the friction and windage loss, the brush-friction loss under the condition of test, the I^2R losses in the armature circuit windings at light load, and the brush-contact loss. To determine the sum of the friction and windage loss, the brush friction loss under the condition of test, and the rotational core loss, it is necessary to subtract the I^2R losses of the armature circuit windings and the brush-contact loss from the input power.

5.6.3 Retardation Method. The retardation method is used when measurement of input power is inconvenient and is most commonly employed for tests made after installation. It is especially adaptable to machines of large inertia. The method consists of bringing the machine up to a speed slightly in excess of rated, but below its maximum safe speed, shutting off the power supply and making simultaneous readings of speed and time as the machine speed decreases. With these relationships and the calculated or measured moment of inertia of the rotating mass, the total loss may be determined by the following formula:

$$P = c \cdot J \cdot n \cdot \frac{dn}{dt} \cdot 10^{-6}$$

where

P = power loss (kW) at speed n
n = rotational speed (r/min)
$\frac{dn}{dt}$ = rate of deceleration (r/min)/s at speed n
J = moment of inertia of rotating parts
c = constant related to units used:

J	c
k·m² (SI units)	10.97
lb·ft² (numerically equal to wk^2 [lb·ft²])	0.4621
slug·ft²	14.88

If the armature terminals are open-circuited, the total loss includes the friction and windage of all mechanically connected apparatus together with the open-circuit core loss corresponding to the value of the field current held. The open-circuit core loss curve may be segregated from the friction and windage loss by taking readings at various values of field current and subtracting the loss when the field current is zero.

5.7 Load Test of Fractional-Horsepower Motors. Load performance for fractional-horsepower motors should be measured by means of a dynamometer, torquemeter, or prony brake.

On continuous-rated motors, the machine should be operated at rated load until essentially constant temperature is attained prior to test. On short-time-rated motors, the rated load should be carried for the period of time for which it is rated prior to making the load test. Start the load test at two and one-half to three times rated load current and take readings at approximately 25% steps down to no-load, or in the case of a series motor, to the maximum safe speed. Readings should be taken at each load of line voltage, line (input) current, shunt-field current (whenever terminals are provided), speed, and torque.

5.8 Load Test of Integral-Horsepower Motors

5.8.1 Loading. Small integral-horsepower motors can be loaded using a load generator, dynamometer, or prony brake with or without a torquemeter.

On large integral-horsepower motors, means for direct measurement of output torque are usually unavailable. The pump-back method (see 5.4.4) can be used, provided that two machines of the same type and rating are available for the test. Where the same type and rating of machine is not available, the load test may be run by loading the test motor using a calibrated direct current generator, or the motor may be run at rated speed as a short-circuited generator at very low field current, driven by a small motor. The losses under short circuit condition are primarily I^2R losses. Only very limited load data can be obtained by the short-circuit method.

WARNING: *During short-circuit tests, the air gap flux is very low and the brush position may have an adverse effect on the load stability of the machine; a load current runaway condition may occur. The circuit should be protected by a quick-acting circuit breaker of high interrupting capability. If instability should occur, readjust the brush position toward the neutral position. Failure to observe these precautions may result in injury to personnel and damage to equipment.*

5.8.2 Test Procedure. On continuous-rated motors, the machine should be operated at rated load until essentially constant temperature is attained prior to test.

On short-time-rated motors, the rated load should be carried for the period of time for which it is rated prior to making load test.

(1) For motors with no speed range by field weakening, the load test should be started at one and one-half times rated load current and readings taken in approximately 25% steps down to no load. In the case of series-excited motors, the load should be decreased in 25% steps, until maximum safe speed is attained.

(2) For motors intended for speed adjustment by field weakening, the load test may be performed at both base speed (full field) and maximum rated speed (weak field). Proceed as in (1) except note motor speed stability at maximum speed operation.

5.8.3 Readings. The same readings should be made as indicated in 5.4.3 except that torque measurements may be omitted in load tests of a routine nature.

6. Temperature Tests

6.1 Purpose. Temperature tests are made to determine the rise in temperature above the ambient temperature of specified parts of the direct-current machine, when subjected to rated load. Guides for the test procedures and the treatment of data are as follows:

6.2 General Instructions. The machine being tested should be assembled with all parts, covers, and accessories that will affect the temperature rise. The enclosure should be in accordance with the guarantee.

The machine under test should be protected from drafts of air issuing from adjacent machines and other sources which may affect the ambient temperature and the temperature rise of the machine under test. Ample floor space should be allowed for free circulation of air. Small changes in the natural ventilation may greatly affect the temperature rise.

The machine should be correctly adjusted for commutation and regulation before heating tests are undertaken.

On rectified power, motor temperature tests should be conducted using the type of rectified power for which the motor is intended or the one on which the rating is based. If a suitable rectified-power source is not available, an indication of motor heating can be obtained by using direct-current-armature power and maintaining the armature current at the rms value anticipated in rectified service. It should be noted, however, that because of additional copper and iron losses, machine temperatures in actual rectifier service will be higher than the test values, particularly in the case of enclosed machines.

6.2.1 Instrumentation. The temperature measuring instruments should be in accordance with IEEE Std 119-1974 [8]. Before commencing any heating tests, all instruments should be checked to minimize errors or stray field effects.

6.3 Methods of Temperature Measurement. Usually the most dependable method of temperature measurement of machine windings is by observing changes in the resistance of the windings or portions thereof. Typically, surface temperature measurements of windings are markedly cooler than the average winding temperature. Accordingly, winding temperature limits shall take into account the method of measurement.

6.3.1 Winding Temperature Measurement by Resistance. This method consists of the determination of temperature by comparison of the resistance of the winding, or of part of the winding, at the temperature to be determined with the resistance at a known temperature using the equation given in 4.2.1.

6.3.1.1. For the stationary field windings, there is little difficulty in obtaining satisfactory results by straightforward methods as outlined in 4.2. Usually the voltage-drop method will give best results. It is recommended that the same instruments be used for hot and cold measurements. This will minimize instrumentation error. Alternatively, using a double bridge or equivalent, cold and hot resistance measurements may be taken on low-resistance stationary windings before and after the test using the techniques described in 6.3.1.2.

6.3.1.2 For armature windings, cold and hot resistance measurements of the winding or a portion thereof should be taken using a suitable instrument such as a Kelvin double bridge or using the voltage-drop method. For cold resistance measurements, the machine should have been at rest for a sufficient length of time so that the complete rotor has equalized to one temperature. The surface temperature should be measured at the time the cold resistance measurement is made.

For the double-bridge method, the terminals of the bridge should be connected to two commutator segments located between adjacent brush studs and separated by a minimum of one half the space between the studs. Care shall be taken to reduce the contact resistance to a negligibly low value. The particular segments used should be marked.

For the voltage-drop method, a current of not more than 10% of the rated value should be passed through the brushes of the machine. The potential drop should be measured using a millivoltmeter with the terminals connected to two commutator segments located between adjacent brush studs and separated by a minimum of one half of the distance between the studs. Connections to the segments should be made by pressing sharp voltmeter leads into the commutator segments so as to penetrate any surface oxide film that may be present. The segments contacted should be marked.

On large machines where positioning the rotor is difficult, several positions on the commutator should be available for use in making the above measurements. This will ensure that at least one pair of marked segments are located between adjacent brush studs when the rotor stops at the end of the heat run.

After the cold resistance has been determined, the armature should be rotated at least one revolution and returned near its original position. The cold resistance should be remeasured again. If it does not agree with the initial reading within the accuracy of measurement, the cause of the discrepancy shall be found, corrected, and a repeatable measurement obtained. For best results, the cold resistance and the hot resistance should be measured between the same set of marked commutator segments.

With reduced accuracy, it is not necessary to use the above marked-bar method whenever the resistance is repeatable with any position of the rotor provided the same segment spacing is employed.

6.3.2 Surface Temperature Measurements of Components. This method consists of the determination of temperature of machine parts, including but not limited to the windings, by suitable means such as thermometers, thermistors, or infrared temperature detectors; any of these instruments being applied to the hottest parts readily accessible without alteration of the machine structure. The following temperature readings, if taken, should be measured as described below.

6.3.2.1 Windings (Stationary). On integral-horsepower machines, temperature sensors, if used, should be placed on at least one main-field and one commutating-field coil on each side of the machine. Several sensors should be placed on each coil. Where size and the accessibility of the machine make it impractical, the number of locations may be reduced.

On fractional-horsepower machines, the same procedure should be followed except one temperature sensor per pole should be used. It should be located as far in between the poles at the top of the machine as practical. Care should be taken to place the sensors so as not to be cooled by the ventilating air and so as not to affect the air flow substantially. Also, for these machines, the temperature of the top of the frame should be measured. This is particularly important during tests taken on rectifier power.

6.3.2.2 Bearings. (1) *Ball or Roller Type.* Temperature readings should be taken on the stationary race if possible. If not, the housing temperature readings should be taken.

(2) *Sleeve Type.* Temperature readings should be taken as near as possible to the bearing lining surface.

(3) *Lubricant.* It is customary to measure the temperature of the oil lubricants. Reading should be taken in the reservoir. With forced-lubricated assemblies, ingoing and outgoing temperature readings should be taken.

6.3.3 Measurement of Ambient Temperatures. The procedure to be followed in measuring the ambient temperature is given in IEEE Std 119-1974 [8].

On open machines, the cooling-air temperature should be measured by means of several temperature sensors placed at different points around the machine and halfway up above the base. These devices should be protected from abnormal drafts and heat radiation. They should be located in the path of the cooling air. When circulation of cooling air is restricted by surroundings, in the test area, the temperature of the rotor shall be referred to the weighted mean of all the cooling-air temperatures.

For enclosed, separately ventilated machines, the cooling air shall be measured by temperature sensors placed in the cooling air ducts at the intake of the machine.

The value to be adopted for the cooling-air temperature during a test is the average of all the cooling-air temperature measurements taken at equal intervals of time during the last hour of the test or, in the case of time-limited test, during the last quarter of the duration of the test.

6.4 Test Procedure. The machine may be loaded by one of the methods outlined in 5.4.2. The test shall be made at rated voltage and speed. The loading may be determined by direct measurement of the output or input. A machine having more than one rating shall be tested at the rating which produced the greatest temperature rise. In cases where this cannot be predetermined, the machine shall be separately tested at each rating.

6.4.1 The test shall be continued for the specified time (for machines not continuous rated) or until constant temperatures have been reached. Unless otherwise specified, a short-time test shall commence only when the machine parts are within 5 °C of the ambient temperature.

6.4.2 On continuous-rated machines when a long time is required to attain steady temperatures, reasonable overloads during the preliminary heating period are permissible to shorten the time of the test.

6.4.3 On continuous-load tests, readings should be taken at least once every 30 min until all temperature rises do not vary more than 2% for three consecutive half-hourly readings. On load tests with time limits, the readings should be taken as often as practicable and at intervals which are consistent with the time rating.

6.4.4 Precautions should be taken to minimize the stopping period and to maintain the temperature during the stopping period, as for example, by maintaining armature current. It is recommended that means be used to limit the time required to take the first resistance or temperature reading to a value not exceeding that specified for the given rating as follows:

Rating	Time
50 kW and less	60 s
50 kW through 200 kW	90 s
Above 200 kW	120 s

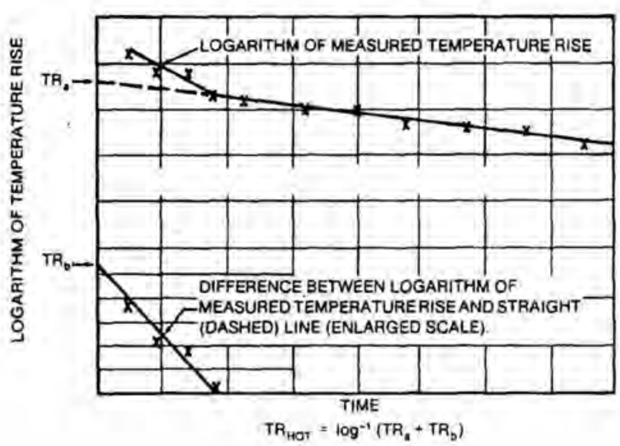
Measurements of the armature winding temperature at shutdown should be taken as described in 6.5.

6.5 Armature Shut-Down Temperature Determination

6.5.1 Resistance Measurements. First readings of hot armature resistance should be taken within the time limits given in 6.4.4. The readings should be taken as frequently as practical. The readings should be taken for a period of not less than 10 min after shutdown. Time shall be measured from the instant of shutdown.

The hot-temperature rise will be deemed to be the value determined by extrapolation of the data to the instant of shutdown. The extrapolation can be made using uniformly scaled curve paper by plotting versus time the values of the logarithm of temperature rise as determined from the measured resistance data. An example of such a plot is shown in Fig 2. A straight line is drawn

Fig 2
Time-Temperature Plot Armature



through the test points disregarding the earliest points. A second straight line is drawn through a plot of the difference between the earliest test points and the first straight line. The initial temperature rise of the winding or winding part measured is derived from the antilogarithm of the sum of the intercepts of the two straight lines with the Y axis.

6.5.2 Surface Measurements.

6.5.2.1 Windings (Rotating). If surface temperature measurements of windings are taken, immediately on shutdown temperature sensors should be placed as follows: on the armature core at the tooth tops, on the conductors in the end windings, where they are not covered by binding bands, and on the binding bands. These sensors should be equally divided between the commutator end and the drive end of the machine whenever possible.

6.5.2.2 Commutator. Immediately on shutdown, thermometers or other temperature sensors, or both, should be placed on the commutator surface. On machines with tandem commutators or multiple commutators, each section of the commutator should be treated as a separate commutator.

6.5.2.3 Determination of Hot Surface Temperature. The hot surface temperature will be deemed to be the value of the temperature readings extrapolated to the instant of shutdown in the manner described in 6.5.1. If the temperatures as read indicate a temperature rise after the first readings followed by declining values, the maximum temperature read is to be considered the temperature at shutdown.

6.6 Temperature Rise. Machines should be given heating tests under standard conditions as provided by 4.1. When the machine is ventilated by the immediate surrounding air, the temperature rise is the observed machine temperature minus the ambient air temperature. When the machine is ventilated by the air obtained from a remote source, the temperature rise is the observed machine temperature minus the average in-going air temperature. The observed machine temperature shall be the maximum reading obtained at the time of shutdown.

7. Miscellaneous Tests

7.1 Audio-Noise Test. Regarding the recommended test procedure for the measurement of airborne noise emanating from rotating electric machinery see IEEE Std 85-1973 [6].

On rectified power, motors exhibit significantly different noise characteristics than they do on dc power. For that reason, if noise is considered important, measurement should be made considering the following criteria.

(1) Noise amplitude and the frequencies produced will be determined by the rectified power source characteristics, including those associated with the magnitude of the armature circuit current ripple. This noise is in addition to the noise associated with operation on dc power.

(2) The maximum noise level resulting from rectified power will generally occur when the armature circuit ac ripple current is a maximum and when the main field windings are excited.

(3) The objectional aspect of noise may be more dependent on frequencies than on magnitude.

(4) The phase balance of the power supply affects the noise significantly. The current wave shape should be observed and any unbalance eliminated.

7.2 Electromagnetic Interference Test. (This test is not normally required for industrial motors.)

See ANSI C63.4-1981 [1]. The methods described in this standard should be used. The limits shall not apply.

7.3 Voltage Wave Shape. This test is to determine the variation in the terminal voltage from pure direct-current potential generated by a dc machine but excluding all high-frequency voltages generated by brush sparking (visible and invisible). The measuring equipment should have frequency response characteristic that is flat within 3 dB to a frequency equal to three times the commutator segment frequency. The ripple voltage expressed as percent is equal to 100 times the maximum peak-to-peak voltage variation divided by twice the average test voltage.

This test should be taken at rated speed, rated voltage, and no-load. If specified, this test may also be taken at specific loads, but provision shall be made to ensure that no harmonic content is contributed by the load device.

The peak-to-peak voltage variation may be measured using a cathode-ray oscilloscope, a suitable oscillograph or an electronic peak-reading voltmeter.

7.3.1 Cathode-Ray Oscilloscope or Oscillo-

graph Method. Readings of maximum peak-to-peak voltage variations can be measured with the oscilloscope or oscillograph connected across the terminals of the machine through a suitable low-pass filter. The filter should have a cut-off frequency not less than 125% of commutator segment frequency. A uniform cutoff frequency of 16 000 Hz is suggested. This filter should have negligible attenuation up to 80% of the cutoff frequency. A photograph of the voltage waveform may be taken to facilitate accurate reading. A direct-current voltage from a suitably calibrated source can be used to calibrate the instrument.

7.3.2 Electronic Peak Reading Voltmeter Method. Peak voltage readings can be taken with the peak reading voltmeter in series with a suitable capacitor (at least 4.0 μF) connected across the terminals of the machine. Readings should be taken with the voltmeter successively connected for each of the two polarities. The higher of the two readings shall be used.

CAUTION: *Any resonance of the measuring circuitry must be avoided.*

7.4 Exciter Response Measurement. The main exciter response ratio, formerly *nominal exciter response* is defined in ANSI/IEEE Std 100-1984 [4]. It is not applicable to electronic exciters or to exciters having series fields of significance.

The test to determine the main exciter response ratio should be taken at rated speed and with no load on the exciter. A permanent record recording device having a frequency response of ten or more times that of the exciter should be used. If there is no internal timing means in the recording device, one element should be connected to a suitable oscillator or other timing device of known frequency for a timing wave on the oscillogram. The other recording channel should be connected across the armature terminals of the exciter.

The exciter should be adjusted to the nominal *exciter ceiling voltage* as defined in ANSI/IEEE Std 100-1984 [4], using an adjustable resistor connected in series with the short-circuited exciter-field rheostat. Next, the exciter-field rheostat should be adjusted to yield the nominal *rated-load field voltage* of the generator. The recording of the exciter armature voltage should be started following which the field rheostat should be short circuited abruptly. The record should be taken for at least the first second of the voltage buildup.

The results through the first half-second of the transient should be plotted as shown in Fig 3. The line EC is drawn so that the area EBC is equal to the area beneath the exciter voltage buildup curve EBD. The main exciter response ratio is:

$$\text{Nominal exciter response ratio} = \frac{2BC}{AB}$$

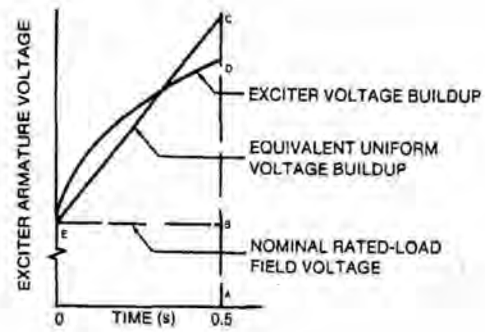


Fig 3
Nominal Exciter Response

7.5 Winding Inductance Measurement

7.5.1 Armature Circuit Inductance Test of Shunt- and Compound-Wound Machines

7.5.1.1 Unsaturated Inductance. This test is to be taken by applying single phase 50 Hz or 60 Hz alternating current to the armature circuit terminals of the machine, including all series-connected field windings, if any. The shunt-field winding should be short-circuited so as to avoid the development of high voltages within the winding. The inductance, so determined, is generally representative of the inductance at other frequencies and with direct current and alternating current components present.

WARNING: *If the shunt-field circuit is open, high voltages may occur within the shunt-field winding and at the terminal which may cause damage to the machine and injury to test personnel.*

The armature should be locked to prevent motion. Normal carbon brushes can be used if the alternating current is limited to approximately 20% of the current rating of the machine so as to avoid overheating of the brushes or the commutator during the brief tests. The brushes should be fitted and inspected before the test is begun.

With the alternating current adjusted successively in three approximately equally spaced steps, the largest value not exceeding 20% of the current rating of the machine, voltage measurements should be taken across the complete armature circuit and across the components thereof. The phase angle between the current and the various voltages should be observed using suitable means such as an oscilloscope. Alternatively, measurements using a wattmeter can be used in the determination of the reactive component of impedance and the associated inductance. The inductance of the complete armature circuit and of the various components, from the average of the test data, is

$$L = \frac{V \cdot \sin\theta}{I \cdot 2\pi \cdot f}$$

where

L = inductance (henrys)
V = voltage (volts)
I = current (amperes)
θ = phase angle between voltage and current
f = frequency (hertz)

7.5.1.2 Saturated Inductance. This test is the same as the unsaturated test except that the shunt field is excited from a direct-current power supply as described in 3.5.1 at rated shunt-field current or, in the absence of a current rating, at the current corresponding to the full field, full-load rating of the machine.

7.5.2 Armature Circuit Inductance Test of Series-Excited Machines (Including Series Field). The armature circuit inductance of series-excited machines varies widely with frequency and with the magnitude of the dc and ac components of current. Accordingly, the inductance values determined from the tests described above are of value for analytical and for manufacturing control purposes but are not a measure of machine inductance at rated load and at other than the test frequency. Useful measurements of the saturated inductance of the armature can be taken excluding the series-field winding which, instead, is excited at rated current using a direct-current power supply as described in 3.5.1. The saturated inductance, so determined, does not include the inductance contributed by the series field which shall be determined analytically.

7.5.3 Shunt-Field Inductance Test. In the test and calculation procedures detailed below, the shunt-field inductance is determined from the rate of buildup of shunt-field current upon abrupt application of voltage to the shunt-field terminals with the machine driven at rated full-field speed and with the armature open-circuited. Also, what is termed the effective inductance is calculated from the rate of buildup of direct-axis flux as indicated by the generated armature voltage measured at the brushes. Both inductance values are evaluated as the product of the shunt-field resistance and time to achieve 63.2% of the ultimate value of the variable.

$$L_f = R_f \cdot T_{1_f}$$
$$L_{f_{eff}} = R_f \cdot T_{v_a}$$

where

L_f = shunt-field inductance (henrys)
$L_{f_{eff}}$ = shunt-field effective inductance (henrys)
R_f = dc shunt-field resistance (ohms)
T_{1_f} = time to achieve 63.2% of field-current change (seconds)
T_{v_a} = time to achieve 63.2% of armature-voltage change (seconds)

7.5.3.1 Unsaturated Inductance. With the machine driven at rated full-field speed, the shunt field should be excited from a voltage source having a regulation at rated full-field excitation of the test machine of less than 2%. Cycle the shunt-field excitation voltage twice between the value yielding rated armature voltage and zero and then reduce the armature voltage to approximately 50% of rated value. After noting the shunt-field voltage, reduce it to zero and open the field circuit. Adjust the exciter voltage to the preestablished value. Observe and record the shunt-field voltage and current, the armature voltage and speed upon closure of the shunt-field circuit.

7.5.3.2 Saturated Inductance. Establish the shunt-field excitation circuitry shown in Fig 4 so as to allow an abrupt change in excitation voltage between values yielding approximately 90% and 110% of rated armature voltage.

With switch SW1 closed, adjust the shunt-field supply voltage, V_f, to produce a field current yielding 110% of rated armature voltage. With switch SW1 opened, cycle R_{ext} twice between the values yielding 90% and 110% of rated armature voltage, finishing at the 90% value. Observe and record the shunt-field voltage and current, the armature voltage and speed upon closure of the switch, SW1.

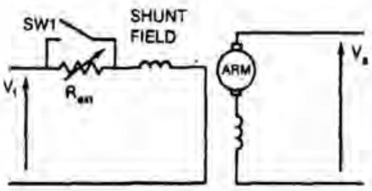


Fig 4
Test Circuitry for Saturated Shunt Field Inductance Measurement

7.6 Shaft Current. Shaft current may cause bearing troubles in motors or in connected equipment. Bearings or shaft journals, or both, which are damaged by shaft current, will have a frosted or speckled appearance. The lubricating oil or grease will contain fine metallic particle contamination and will change color.

On rectified power, motors may be subjected to shaft current depending on the characteristics and grounding of the power supply involved and the electromagnetic and mechanical design of the motor.

Causes of Shaft Current. Shaft current is produced by three different causes:

(1) Circulating current may result from an electromotive force generated in the shaft. This voltage is generated by any unsymmetrical distribution of magnetic flux between poles in either the stationary or rotating yokes which results in net flux that encircles the shaft and is alternating in polarity. This alternating flux generates an ac electromotive force between the ends of the shaft. If this electromotive force is sufficient to break down the dielectric strength of the oil film, shaft current will flow if an external electric circuit is provided between bearings.

(2) Localized current may result in magnetic flux circulating through the shaft and bearings. If any net current encircles the shaft, such as resulting from the stator winding connections, a magnetomotive force is developed between the ends of the shaft. The resulting magnetic flux passes through the bearings and the external supporting structure of the machine. Rotation of the shaft generates a homopolar dc voltage around the shaft bearing journal interface loop which, if sufficient to break down the dielectric strength of the oil film, results in damaging localized current in the bearing. Because of magnetic saturation of the shaft or of the associated magnetic circuit and because the journal speed is limited for good bearing operation, the direct voltage can very seldom exceed a small fraction of a volt.

(3) On rectified power, bearing current may result from the capacitive coupling between the armature winding and its supporting structure particularly with sleeve bearing motors. The alternating component of voltage between the windings and ground results in a leakage current which passes through the bearings in parallel to ground. Insulation of a single bearing, or a bearing pedestal, as is commonly done at one end of large machines, does not prevent the possible flow of capacitive current at other uninsulated bearings. Damaging current flows if the peak shaft voltage exceeds the breakdown strength of the oil film in the bearing. Only an effective shunting of the path through the bearing can prevent damage. A set of properly maintained shaft grounding brushes riding on the rotating shaft surface will provide the necessary shunting path and prevent bearing damage.

7.6.2 Tests for Shaft Current

7.6.2.1 Circulating Current Due to Shaft Electromotive Force. This test should be taken on the machine at no-load, rated voltage, and at both base and maximum speed. The external electric circuit formed by the bearing supporting structure, bearings, and shaft, shall be open-circuited.

(1) At each of the above conditions, measure the electromotive force generated between the ends of the shaft with an ac millivoltmeter. A 100 mV full-scale instrument is usually adequate. The electronic or thermal type instrument is satisfactory for this test.

CAUTION: *The contacting probes or brushes should ensure good metal-to-metal contact and repeatable results should be obtained.*

(2) At each of the above conditions, measure the current with a 60 A or larger alternating-current ammeter with each lead 3 m (10 ft) in length of No 4 wire or larger connected between the ends of the shaft.

CAUTION: *The contacting probes and the shaft shall have a very low-resistance junction. The magnitude of the current will frequently be in the low range of the instrument scale. The scale reading should be recorded. The actual magnitude shall be determined by appropriate calibration. A lower reading instrument will have too high an impedance to give good results.*

7.6.2.2 Local Current Due to Shaft Magnetomotive Force. The test should be taken on the machine at rated load, rated voltage, and maximum rated speed. The magnetic circuit formed by the bearing supporting structure, bearings, and shaft should simulate the actual application as closely as practical. Measure the voltage residual under the above condition with a direct-current millivoltmeter. A 100 mV full-scale instrument is usually adequate. The instrument leads fitted should contact the surface of the shaft with low-resistance probes at each side of the bearing housing. This test should be repeated for each bearing.

7.6.2.3 Bearing Current Due to Winding-to-Ground Capacitance. On rectified power, possible shaft potentials can be detected by measuring the shaft-to-ground ac potential with an oscilloscope or an electronic ac voltmeter with the machine powered under normal operating conditions and the shaft grounding brushes raised. A voltage level of less than 50 V peak to peak can be considered normal. If the reading shows a higher voltage level, the effectiveness of the grounding brushes becomes greatly reduced and the hazard to personnel increases. Accordingly, the integrity of the power supply should be investigated. With the shaft grounding brushes lowered and with proper maintenance, the peak-to-peak voltage should diminish to less than 5 V under normal operating conditions.

CAUTION: *The above observations should be made quickly so as to avoid damage to the shaft and bearing journals.*

7.7 Moment of Inertia Measurement. Two methods are described below for determining the moment of inertia of direct-current machines. The first method is suited to the testing of assembled machines—particularly large machines. The second method involves testing of the armature alone.

7.7.1 Retardation Test Method

7.7.1.1 Determine the friction and windage losses of the machine, including brush friction, using the methods of measurement described in 5.6. Test at several speeds and plot the sum of these losses as a function of speed as shown in Fig 5(a).

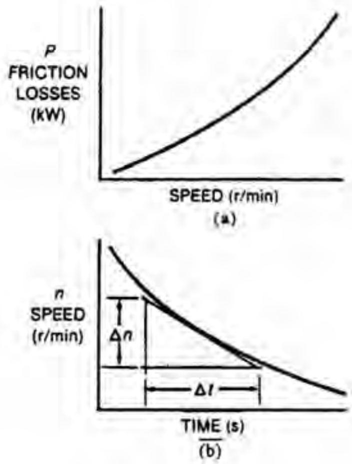


Fig 5
Steps in Derivation of Moment of Inertia by the Retardation Method

7.7.1.2 With the machine uncoupled, increase the speed to the maximum rated value and remove armature- and field-excitation power. Measure the speed as a function of time as shown in Fig 5(b) and, from the slope of the curve, derive the rate of change of speed as a function of speed.

7.7.1.3 Derive the moment of inertia from observations at several speeds using the following equation:

$$J = \frac{P \cdot 10^6}{c \cdot n \cdot \frac{dn}{dt}}$$

where

J = moment of inertia
P = friction losses (kW at speed n)
n = rotational speed (r/min)
$\frac{dn}{dt}$ = rate of deceleration, (r/min)/s at speed n
c = constant related to units used

J	c
kg · m²	10.97
*lb · ft²	0.4621
slug · ft²	14.88

*Numerically equal to wk^2 (lb·ft²)

7.7.2 Angular Oscillation Test.

7.7.2.1 Suspend the armature with the shaft oriented vertically using two parallel wires as indicated in Fig 6. The wires should be attached

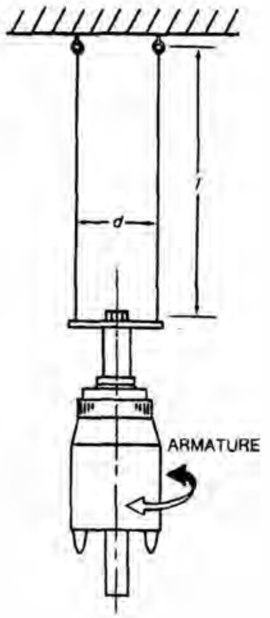


Fig 6
Angular Oscillation wk² Test

diametrically, equally spaced from the centerline of the shaft. The length to separation ratio (l/d) should be approximately ten. Displace (rotate) the armature a small amount from the equilibrium position, and after release measure the frequency of angular oscillation. The moment of inertia is determined from the equation:

$$J = \frac{c \cdot m \cdot d^2}{l \cdot f^2}$$

where

J = moment of inertia
m = armature weight
l = length of wires
d = separation of wires
f = frequency of oscillation in hertz
c = constant related to units used:

J	m	l,d	c
kg·m²	kg	m	$6.2 \cdot 10^{-2}$
*lb·ft²	lb	ft	$2.04 \cdot 10^{-1}$
slug·ft²	lb	ft	$6.33 \cdot 10^{-3}$

*Numerically equal to wk^2 (lb·ft²)

8. Bibliography
(Papers Relating to the Operation of DC Motors on Rectifier Power)

[B1] IEEE Std 62-1978, IEEE Guide for Field Testing Power Apparatus Insulation.

[B2] IEEE Std 120-1955 (R 1972), IEEE Master Test Code for Electrical Measurements in Power Circuits.

[B3] DEWOLF, F. T. Measurement of Inductance of DC Machines, *IEEE Transactions, Power Apparatus and Systems,* vol 98, no 5, 1979, pp 1636 – 1644.

[B4] DEWOLF, F. T. and MICHAEL, R. N. Measurement of Input Power of DC Motors Operated Using Rectifier Power Supplies and Choppers, *IEEE Industry Applications Society Conference Record,* 1978, pp 749 – 754.

[B5] EWING, J. S. Efficiency and Displacement Power Factor of Static DC Drive Systems, *IEEE Industry Applications Society Conference Record,* 1977, pp 917 – 922.

[B6] EWING, J. S. Lumped Circuit Impedance Representation for DC Machines, *IEEE Transactions, Power Apparatus and Systems,* vol 87, no 4, 1968, pp 1106 – 1110.

[B7] HAMILTON, H. B. and STRANGAS, E. Series Motor Parameter Variations as a Function of Frequency and Saturation, *IEEE Power Engineering Society Winter Meeting*, F80 151 – 1.

[B8] KUBLER, E. F. The Armature Current Form Factor of a DC Motor Connected to a Controlled Rectifier. *AIEE Transactions, Power Apparatus and Systems*, vol 78, part IIIA, 1959, pp 764 – 770.

[B9] PFAFF, R. W. Characteristics of Phase-Controlled Bridge Rectifiers with DC Shunt Motor Load. *AIEE Transactions, Applications and Industry*, vol 77, part II, 1958, pp 49 – 53.

[B10] VRANA, V. E. The DC Motor and Thyristor Power Supply, *Westinghouse Engineer*, vol 27, no 4, 1967, pp 98 – 104.

A.2

LM 555

National Semiconductor

February 2000

LM555
Timer

General Description

The LM555 is a highly stable device for generating accurate time delays or oscillation. Additional terminals are provided for triggering or resetting if desired. In the time delay mode of operation, the time is precisely controlled by one external resistor and capacitor. For astable operation as an oscillator, the free running frequency and duty cycle are accurately controlled with two external resistors and one capacitor. The circuit may be triggered and reset on falling waveforms, and the output circuit can source or sink up to 200mA or drive TTL circuits.

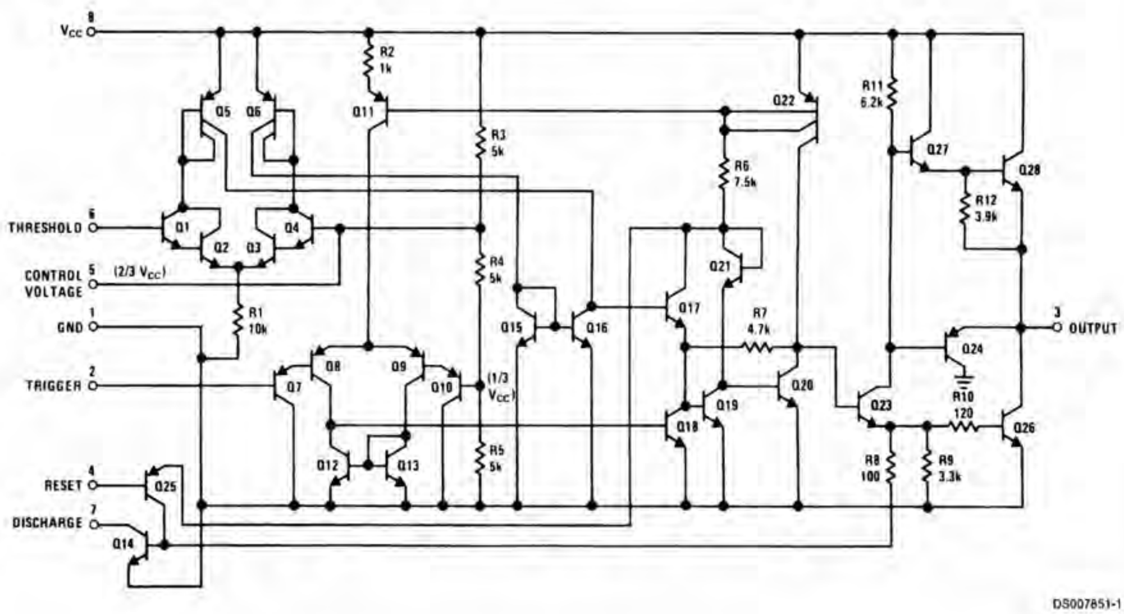
Features

- Direct replacement for SE555/NE555
- Timing from microseconds through hours
- Operates in both astable and monostable modes
- Adjustable duty cycle
- Output can source or sink 200 mA
- Output and supply TTL compatible
- Temperature stability better than 0.005% per °C
- Normally on and normally off output
- Available in 8-pin MSOP package

Applications

- Precision timing
- Pulse generation
- Sequential timing
- Time delay generation
- Pulse width modulation
- Pulse position modulation
- Linear ramp generator

Schematic Diagram

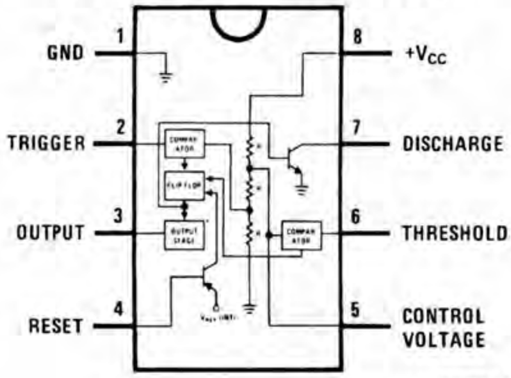


DS007851-1

 DS007851

Connection Diagram

Dual-In-Line, Small Outline and Molded Mini Small Outline Packages



DS007851-3

Top View

Ordering Information

Package	Part Number	Package Marking	Media Transport	NSC Drawing
8-Pin SOIC	LM555CM	LM555CM	Rails	M08A
	LM555CMX	LM555CM	2.5k Units Tape and Reel	
8-Pin MSOP	LM555CMM	Z55	1k Units Tape and Reel	MUA08A
	LM555CMMX	Z55	3.5k Units Tape and Reel	
8-Pin MDIP	LM555CN	LM555CN	Rails	N08E

Absolute Maximum Ratings (Note 2)

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

Supply Voltage	+18V
Power Dissipation (Note 3)	
LM555CM, LM555CN	1180 mW
LM555CMM	613 mW
Operating Temperature Ranges	
LM555C	0°C to +70°C
Storage Temperature Range	−65°C to +150°C
Soldering Information	
Dual-In-Line Package	
Soldering (10 Seconds)	260°C
Small Outline Packages (SOIC and MSOP)	
Vapor Phase (60 Seconds)	215°C
Infrared (15 Seconds)	220°C

See AN-450 "Surface Mounting Methods and Their Effect on Product Reliability" for other methods of soldering surface mount devices.

Electrical Characteristics (Notes 1, 2)

(T_A = 25°C, V_{CC} = +5V to +15V, unless othewise specified)

Parameter	Conditions	Limits LM555C Min	Typ	Max	Units
Supply Voltage		4.5		16	V
Supply Current	V_{CC} = 5V, R_L = ∞ V_{CC} = 15V, R_L = ∞ (Low State) (Note 4)		3 10	6 15	mA
Timing Error, Monostable					
Initial Accuracy			1		%
Drift with Temperature	R_A = 1k to 100kΩ, C = 0.1µF, (Note 5)		50		ppm/°C
Accuracy over Temperature			1.5		%
Drift with Supply			0.1		%/V
Timing Error, Astable					
Initial Accuracy			2.25		%
Drift with Temperature	R_A, R_B = 1k to 100kΩ, C = 0.1µF, (Note 5)		150		ppm/°C
Accuracy over Temperature			3.0		%
Drift with Supply			0.30		%/V
Threshold Voltage			0.667		x V_{CC}
Trigger Voltage	V_{CC} = 15V		5		V
	V_{CC} = 5V		1.67		V
Trigger Current			0.5	0.9	µA
Reset Voltage		0.4	0.5	1	V
Reset Current			0.1	0.4	mA
Threshold Current	(Note 6)		0.1	0.25	µA
Control Voltage Level	V_{CC} = 15V V_{CC} = 5V	9 2.6	10 3.33	11 4	V
Pin 7 Leakage Output High			1	100	nA
Pin 7 Sat (Note 7)					
Output Low	V_{CC} = 15V, I_7 = 15mA		180		mV
Output Low	V_{CC} = 4.5V, I_7 = 4.5mA		80	200	mV

Electrical Characteristics (Notes 1, 2) (Continued)

(T_A = 25°C, V_{CC} = +5V to +15V, unless othewise specified)

Parameter	Conditions	Limits			Units
		LM555C			
		Min	Typ	Max	
Output Voltage Drop (Low)	V_{CC} = 15V				
	I_{SINK} = 10mA		0.1	0.25	V
	I_{SINK} = 50mA		0.4	0.75	V
	I_{SINK} = 100mA		2	2.5	V
	I_{SINK} = 200mA		2.5		V
	V_{CC} = 5V				
	I_{SINK} = 8mA				V
	I_{SINK} = 5mA		0.25	0.35	V
Output Voltage Drop (High)	I_{SOURCE} = 200mA, V_{CC} = 15V		12.5		V
	I_{SOURCE} = 100mA, V_{CC} = 15V	12.75	13.3		V
	V_{CC} = 5V	2.75	3.3		V
Rise Time of Output			100		ns
Fall Time of Output			100		ns

Note 1: All voltages are measured with respect to the ground pin, unless otherwise specified.

Note 2: Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is functional, but do not guarantee specific performance limits. Electrical Characteristics state DC and AC electrical specifications under particular test conditions which guarantee specific performance limits. This assumes that the device is within the Operating Ratings. Specifications are not guaranteed for parameters where no limit is given, however, the typical value is a good indication of device performance.

Note 3: For operating at elevated temperatures the device must be derated above 25°C based on a +150°C maximum junction temperature and a thermal resistance of 106°C/W (DIP), 170°C/W (S0-8), and 204°C/W (MSOP) junction to ambient.

Note 4: Supply current when output high typically 1 mA less at V_{CC} = 5V.

Note 5: Tested at V_{CC} = 5V and V_{CC} = 15V.

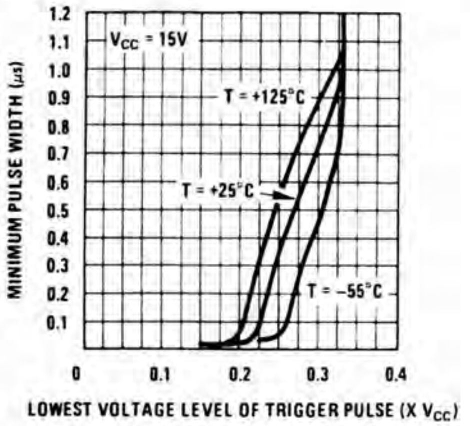
Note 6: This will determine the maximum value of $R_A + R_B$ for 15V operation. The maximum total ($R_A + R_B$) is 20MΩ.

Note 7: No protection against excessive pin 7 current is necessary providing the package dissipation rating will not be exceeded.

Note 8: Refer to RETS555X drawing of military LM555H and LM555J versions for specifications.

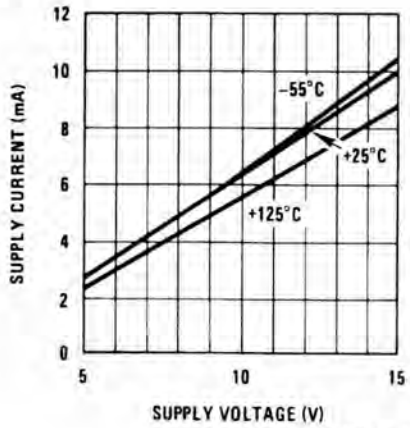
Typical Performance Characteristics

Minimuim Pulse Width Required for Triggering



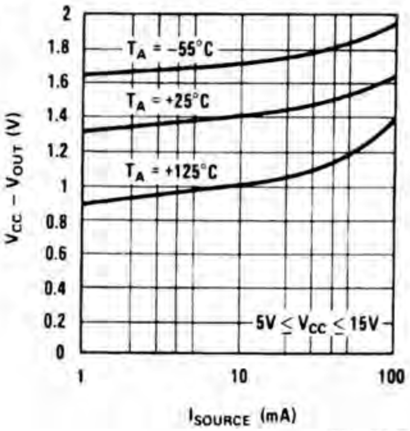
DS007851-4

Supply Current vs. Supply Voltage



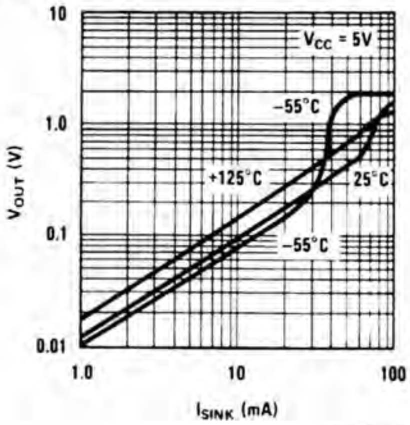
DS007851-19

High Output Voltage vs. Output Source Current



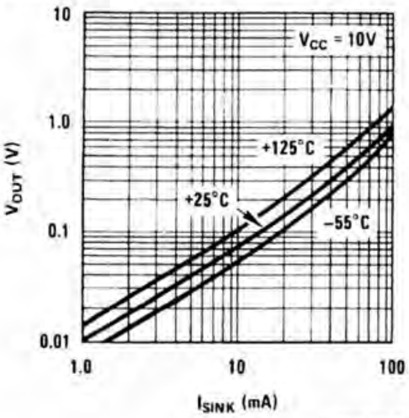
DS007851-20

Low Output Voltage vs. Output Sink Current



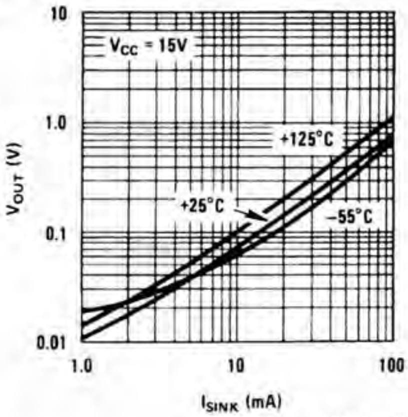
DS007851-21

Low Output Voltage vs. Output Sink Current



DS007851-22

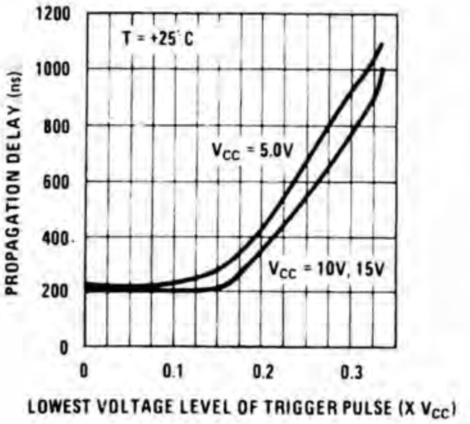
Low Output Voltage vs. Output Sink Current



DS007851-23

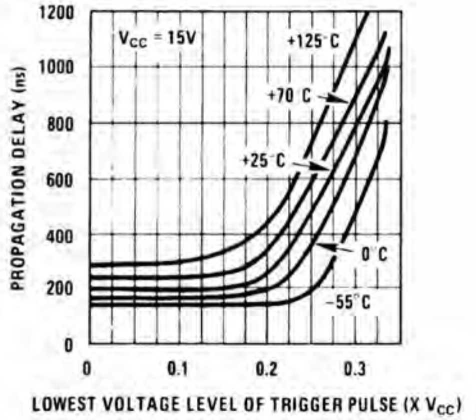
Typical Performance Characteristics (Continued)

Output Propagation Delay vs. Voltage Level of Trigger Pulse



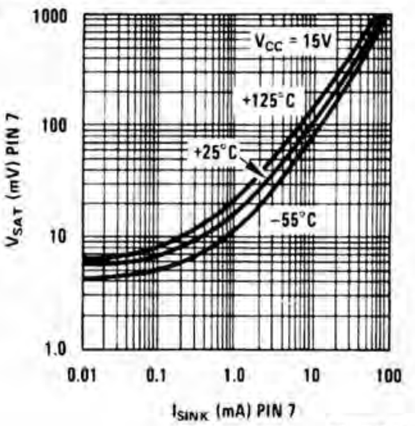
DS007851-24

Output Propagation Delay vs. Voltage Level of Trigger Pulse



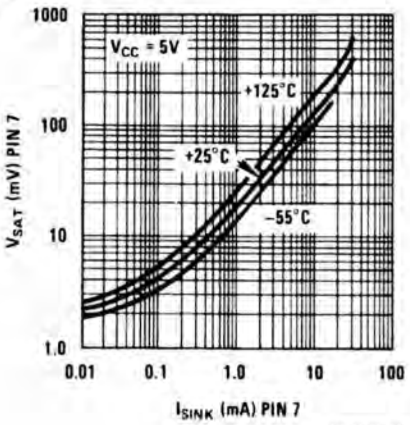
DS007851-25

Discharge Transistor (Pin 7) Voltage vs. Sink Current



DS007851-26

Discharge Transistor (Pin 7) Voltage vs. Sink Current

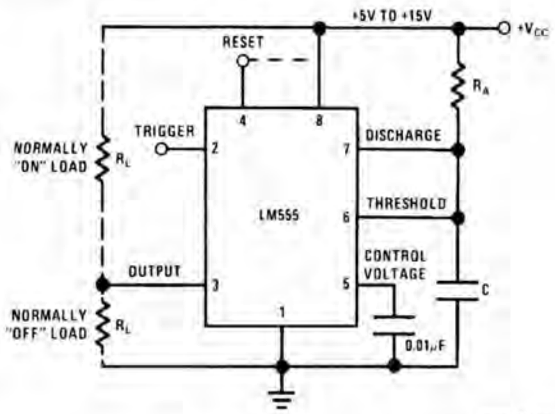


DS007851-27

Applications Information

MONOSTABLE OPERATION

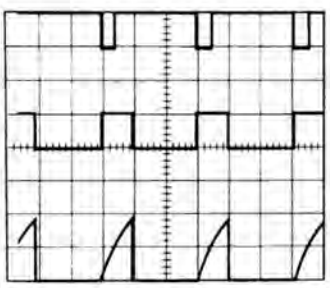
In this mode of operation, the timer functions as a one-shot (*Figure 1*). The external capacitor is initially held discharged by a transistor inside the timer. Upon application of a negative trigger pulse of less than 1/3 V_{CC} to pin 2, the flip-flop is set which both releases the short circuit across the capacitor and drives the output high.



DS007851-5

FIGURE 1. Monostable

The voltage across the capacitor then increases exponentially for a period of t = 1.1 R_A C, at the end of which time the voltage equals 2/3 V_{CC}. The comparator then resets the flip-flop which in turn discharges the capacitor and drives the output to its low state. *Figure 2* shows the waveforms generated in this mode of operation. Since the charge and the threshold level of the comparator are both directly proportional to supply voltage, the timing internal is independent of supply.



DS007851-6

V_{CC} = 5V
TIME = 0.1 ms/DIV.
R_A = 9.1kΩ
C = 0.01µF

Top Trace: Input 5V/Div.
Middle Trace: Output 5V/Div.
Bottom Trace: Capacitor Voltage 2V/Div.

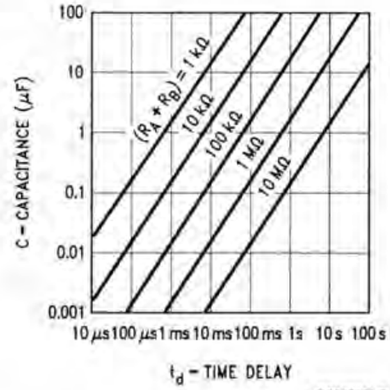
FIGURE 2. Monostable Waveforms

During the timing cycle when the output is high, the further application of a trigger pulse will not effect the circuit so long as the trigger input is returned high at least 10µs before the end of the timing interval. However the circuit can be reset during this time by the application of a negative pulse to the reset terminal (pin 4). The output will then remain in the low state until a trigger pulse is again applied.

When the reset function is not in use, it is recommended that it be connected to V_{CC} to avoid any possibility of false triggering.

Figure 3 is a nomograph for easy determination of R, C values for various time delays.

NOTE: In monostable operation, the trigger should be driven high before the end of timing cycle.

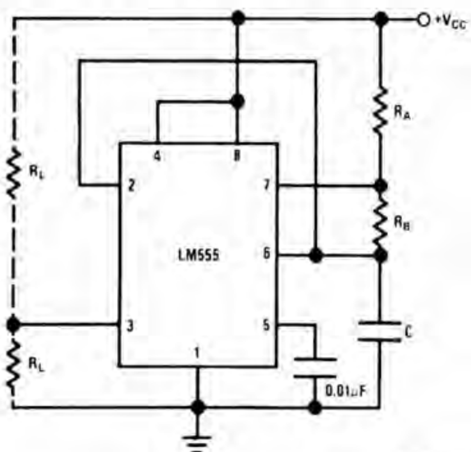


DS007851-7

FIGURE 3. Time Delay

ASTABLE OPERATION

If the circuit is connected as shown in *Figure 4* (pins 2 and 6 connected) it will trigger itself and free run as a multivibrator. The external capacitor charges through R_A + R_B and discharges through R_B. Thus the duty cycle may be precisely set by the ratio of these two resistors.



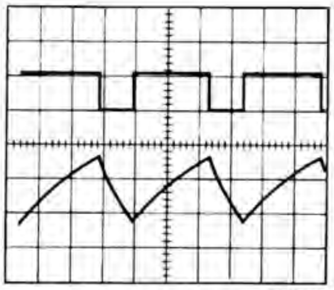
DS007851-8

FIGURE 4. Astable

In this mode of operation, the capacitor charges and discharges between 1/3 V_{CC} and 2/3 V_{CC}. As in the triggered mode, the charge and discharge times, and therefore the frequency are independent of the supply voltage.

Applications Information (Continued)

Figure 5 shows the waveforms generated in this mode of operation.



V_{CC} = 5V
TIME = 20μs/DIV.
R_A = 3.9kΩ
R_B = 3kΩ
C = 0.01μF
Top Trace: Output 5V/Div.
Bottom Trace: Capacitor Voltage 1V/Div.

FIGURE 5. Astable Waveforms

The charge time (output high) is given by:

$$t_1 = 0.693\ (R_A + R_B)\ C$$

And the discharge time (output low) by:

$$t_2 = 0.693\ (R_B)\ C$$

Thus the total period is:

$$T = t_1 + t_2 = 0.693\ (R_A + 2R_B)\ C$$

The frequency of oscillation is:

$$f = \frac{1}{T} = \frac{1.44}{(R_A + 2\,R_B)\,C}$$

Figure 6 may be used for quick determination of these RC values.

The duty cycle is:

$$D = \frac{R_B}{R_A + 2R_B}$$

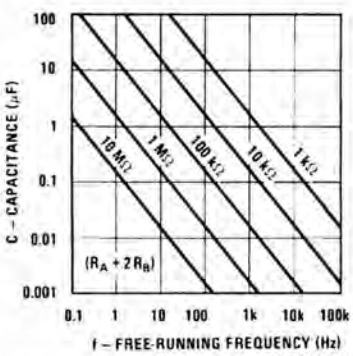
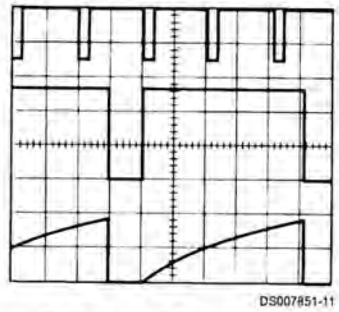


FIGURE 6. Free Running Frequency

FREQUENCY DIVIDER

The monostable circuit of *Figure 1* can be used as a frequency divider by adjusting the length of the timing cycle. *Figure 7* shows the waveforms generated in a divide by three circuit.



V_{CC} = 5V
TIME = 20μs/DIV.
R_A = 9.1kΩ
C = 0.01μF
Top Trace: Input 4V/Div.
Middle Trace: Output 2V/Div.
Bottom Trace: Capacitor 2V/Div.

FIGURE 7. Frequency Divider

PULSE WIDTH MODULATOR

When the timer is connected in the monostable mode and triggered with a continuous pulse train, the output pulse width can be modulated by a signal applied to pin 5. *Figure 8* shows the circuit, and in *Figure 9* are some waveform examples.

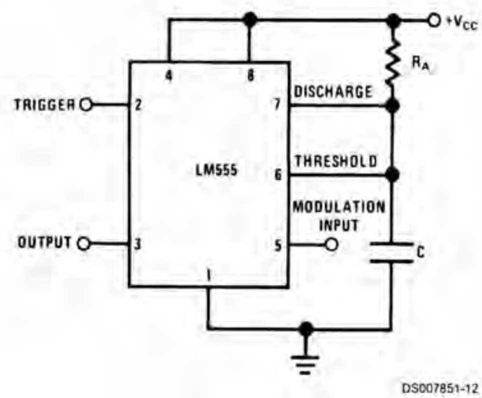
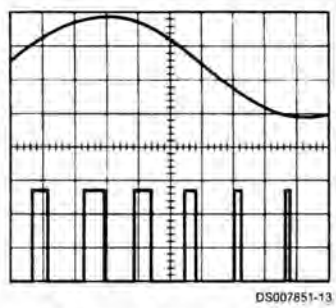


FIGURE 8. Pulse Width Modulator



V_{CC} = 5V
TIME = 0.2 ms/DIV.
R_A = 9.1kΩ
C = 0.01μF
Top Trace: Modulation 1V/Div.
Bottom Trace: Output Voltage 2V/Div.

FIGURE 9. Pulse Width Modulator

A.3

LM 2907

National Semiconductor

May 2003

LM2907/LM2917 Frequency to Voltage Converter

General Description

The LM2907, LM2917 series are monolithic frequency to voltage converters with a high gain op amp/comparator designed to operate a relay, lamp, or other load when the input frequency reaches or exceeds a selected rate. The tachometer uses a charge pump technique and offers frequency doubling for low ripple, full input protection in two versions (LM2907-8, LM2917-8) and its output swings to ground for a zero frequency input.

The op amp/comparator is fully compatible with the tachometer and has a floating transistor as its output. This feature allows either a ground or supply referred load of up to 50 mA. The collector may be taken above V_{CC} up to a maximum V_{CE} of 28V.

The two basic configurations offered include an 8-pin device with a *ground referenced tachometer* input and an internal connection between the tachometer output and the op amp non-inverting input. This version is well suited for single speed or frequency switching or fully buffered frequency to voltage conversion applications.

The more versatile configurations provide differential tachometer input and uncommitted op amp inputs. With this version the tachometer input may be floated and the op amp becomes suitable for active filter conditioning of the tachometer output.

Both of these configurations are available with an active shunt regulator connected across the power leads. The regulator clamps the supply such that stable frequency to voltage and frequency to current operations are possible with any supply voltage and a suitable resistor.

Advantages

- Output swings to ground for zero frequency input
- Easy to use; $V_{OUT} = f_{IN} \times V_{CC} \times R1 \times C1$
- Only one RC network provides frequency doubling
- Zener regulator on chip allows accurate and stable frequency to voltage or current conversion (LM2917)

Features

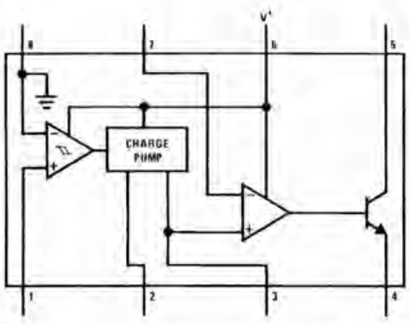
- Ground referenced tachometer input interfaces directly with variable reluctance magnetic pickups
- Op amp/comparator has floating transistor output
- 50 mA sink or source to operate relays, solenoids, meters, or LEDs
- Frequency doubling for low ripple
- Tachometer has built-in hysteresis with either differential input or ground referenced input
- Built-in zener on LM2917
- ±0.3% linearity typical
- Ground referenced tachometer is fully protected from damage due to swings above V_{CC} and below ground

Applications

- Over/under speed sensing
- Frequency to voltage conversion (tachometer)
- Speedometers
- Breaker point dwell meters
- Hand-held tachometer
- Speed governors
- Cruise control
- Automotive door lock control
- Clutch control
- Horn control
- Touch or sound switches

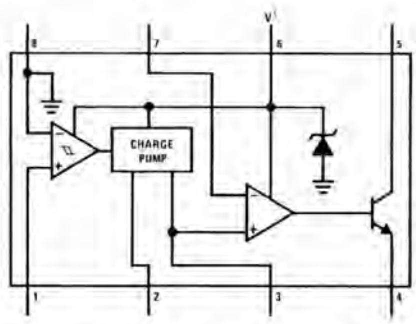
Block and Connection Diagrams

Dual-In-Line and Small Outline Packages, Top Views



00794201

Order Number LM2907M-8 or LM2907N-8
See NS Package Number M08A or N08E

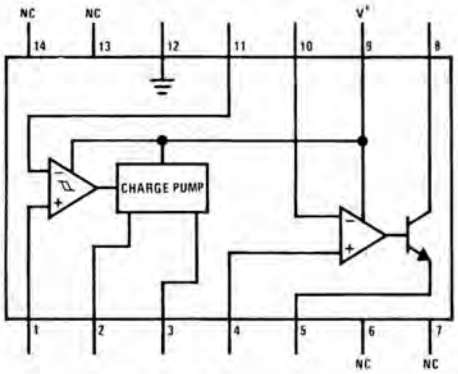


00794202

Order Number LM2917M-8 or LM2917N-8
See NS Package Number M08A or N08E

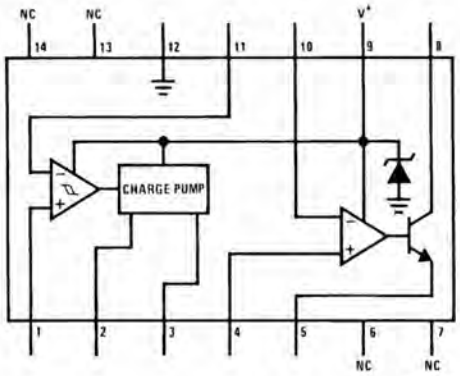
 DS007942

Block and Connection Diagrams Dual-In-Line and Small Outline Packages, Top Views (Continued)



00794203

Order Number LM2907M or LM2907N
See NS Package Number M14A or N14A



00794204

Order Number LM2917M or LM2917N
See NS Package Number M14A or N14A

Absolute Maximum Ratings (Note 1)

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

Supply Voltage	28V
Supply Current (Zener Options)	25 mA
Collector Voltage	28V
Differential Input Voltage	
Tachometer	28V
Op Amp/Comparator	28V
Input Voltage Range	
Tachometer	
LM2907-8, LM2917-8	±28V
LM2907, LM2917	0.0V to +28V
Op Amp/Comparator	0.0V to +28V
Power Dissipation	
LM2907-8, LM2917-8	1200 mW
LM2907-14, LM2917-14	1580 mW
See (Note 1)	
Operating Temperature Range	−40˚C to +85˚C
Storage Temperature Range	−65˚C to +150˚C
Soldering Information	
Dual-In-Line Package	
Soldering (10 seconds)	260˚C
Small Outline Package	
Vapor Phase (60 seconds)	215˚C
Infrared (15 seconds)	220˚C

See AN-450 "Surface Mounting Methods and Their Effect on Product Reliability" for other methods of soldering surface mount devices.

Electrical Characteristics

V_{CC} = 12 V_{DC}, T_A = 25˚C, see test circuit

Symbol	Parameter	Conditions	Min	Typ	Max	Units
TACHOMETER						
	Input Thresholds	V_{IN} = 250 mVp-p @ 1 kHz (Note 2)	±10	±25	±40	mV
	Hysteresis	V_{IN} = 250 mVp-p @ 1 kHz (Note 2)		30		mV
	Offset Voltage	V_{IN} = 250 mVp-p @ 1 kHz (Note 2)				
	LM2907/LM2917			3.5	10	mV
	LM2907-8/LM2917-8			5	15	mV
	Input Bias Current	V_{IN} = ±50 mV_{DC}		0.1	1	µA
V_{OH}	Pin 2	V_{IN} = +125 mV_{DC} (Note 3)		8.3		V
V_{OL}	Pin 2	V_{IN} = −125 mV_{DC} (Note 3)		2.3		V
I_2, I_3	Output Current	V2 = V3 = 6.0V (Note 4)	140	180	240	µA
I_3	Leakage Current	I2 = 0, V3 = 0			0.1	µA
K	Gain Constant	(Note 3)	0.9	1.0	1.1	
	Linearity	f_{IN} = 1 kHz, 5 kHz, 10 kHz (Note 5)	−1.0	0.3	+1.0	%
OP/AMP COMPARATOR						
V_{OS}		V_{IN} = 6.0V		3	10	mV
I_{BIAS}		V_{IN} = 6.0V		50	500	nA
	Input Common-Mode Voltage		0		V_{CC}−1.5V	V
	Voltage Gain			200		V/mV
	Output Sink Current	V_C = 1.0	40	50		mA
	Output Source Current	V_E = V_{CC} −2.0		10		mA
	Saturation Voltage	I_{SINK} = 5 mA		0.1	0.5	V
		I_{SINK} = 20 mA			1.0	V
		I_{SINK} = 50 mA		1.0	1.5	V
ZENER REGULATOR						
	Regulator Voltage	R_{DROP} = 470Ω		7.56		V
	Series Resistance			10.5	15	Ω
	Temperature Stability			+1		mV/˚C
	TOTAL SUPPLY CURRENT			3.8	6	mA

Note 1: For operation in ambient temperatures above 25˚C, the device must be derated based on a 150˚C maximum junction temperature and a thermal resistance of 101˚C/W junction to ambient for LM2907-8 and LM2917-8, and 79˚C/W junction to ambient for LM2907-14 and LM2917-14.

Note 2: Hysteresis is the sum $+V_{TH} - (-V_{TH})$, offset voltage is their difference. See test circuit.

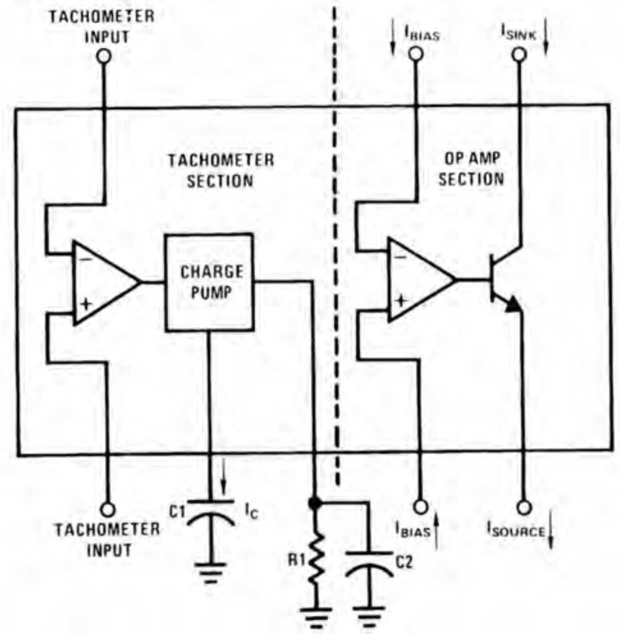
Note 3: V_{OH} is equal to ¾ x V_{CC} − 1 V_{BE}, V_{OL} is equal to ¼ x V_{CC} − 1 V_{BE} therefore $V_{OH} - V_{OL} = V_{CC}/2$. The difference, $V_{OH} - V_{OL}$, and the mirror gain, I_2/I_3, are the two factors that cause the tachometer gain constant to vary from 1.0.

Note 4: Be sure when choosing the time constant R1 x C1 that R1 is such that the maximum anticipated output voltage at pin 3 can be reached with I_3 x R1. The maximum value for R1 is limited by the output resistance of pin 3 which is greater than 10 MΩ typically.

Electrical Characteristics (Continued)

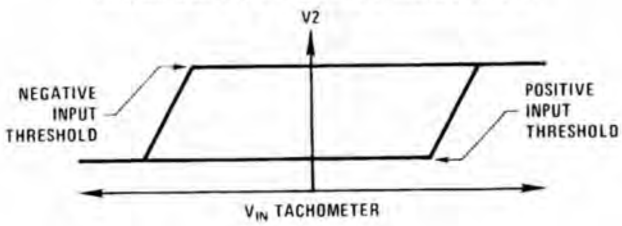
Note 5: Nonlinearity is defined as the deviation of V_{OUT} (@ pin 3) for f_{IN} = 5 kHz from a straight line defined by the V_{OUT} @ 1 kHz and V_{OUT} @ 10 kHz. C1 = 1000 pF, R1 = 68k and C2 = 0.22 mFd.

Test Circuit and Waveform



00794206

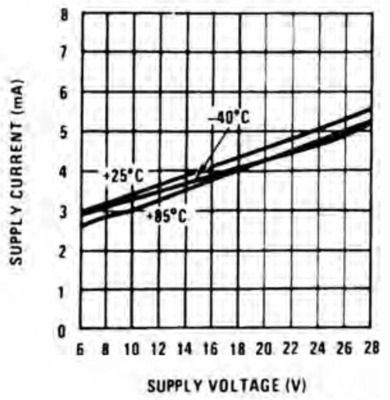
Tachometer Input Threshold Measurement



00794207

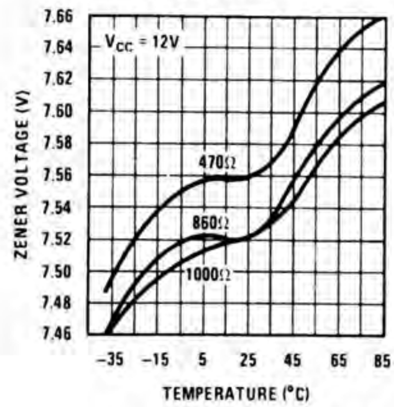
Typical Performance Characteristics

Total Supply Current



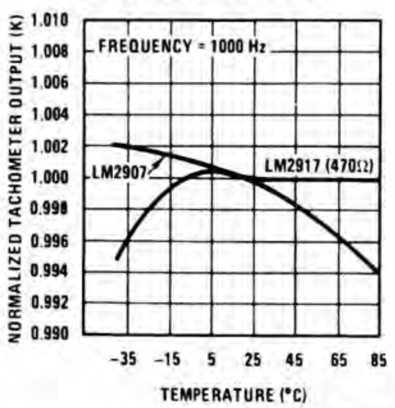
00794240

Zener Voltage vs Temperature



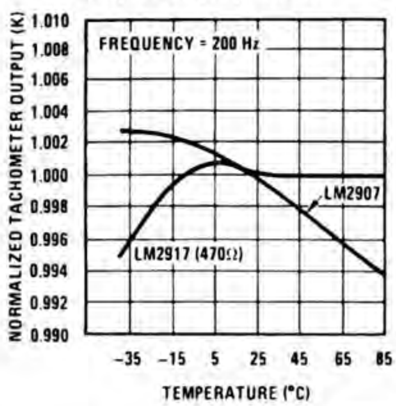
00794241

Normalized Tachometer Output vs Temperature



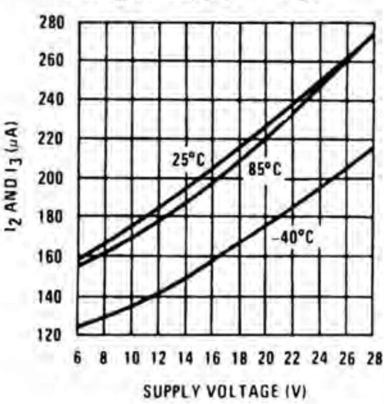
00794242

Normalized Tachometer Output vs Temperature



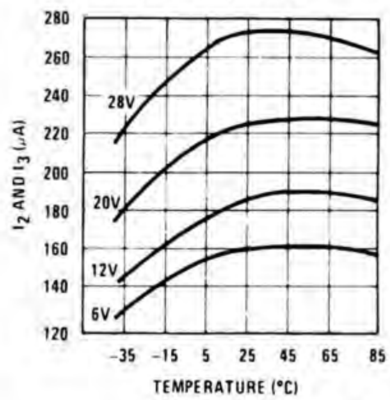
00794243

Tachometer Currents I_2 and I_3 vs Supply Voltage



00794244

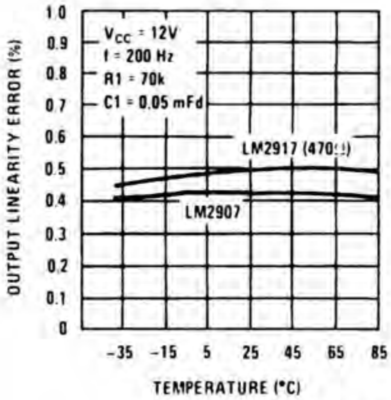
Tachometer Currents I_2 and I_3 vs Temperature



00794245

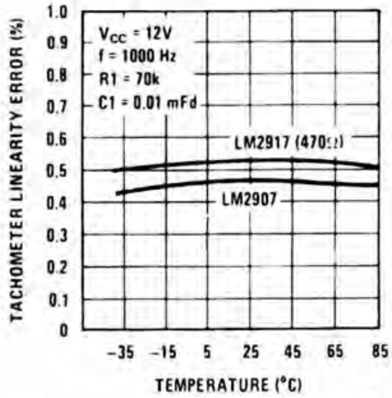
Typical Performance Characteristics (Continued)

Tachometer Linearity vs Temperature



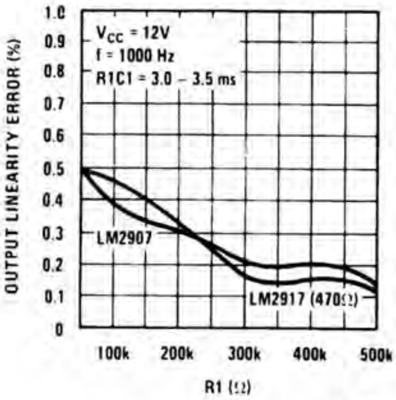
00794246

Tachometer Linearity vs Temperature



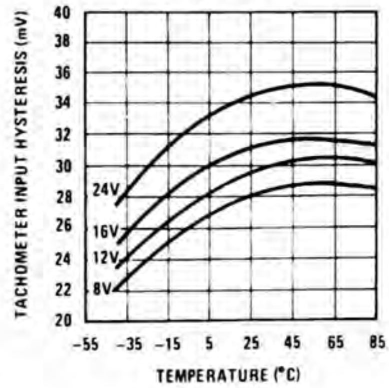
00794247

Tachometer Linearity vs R1



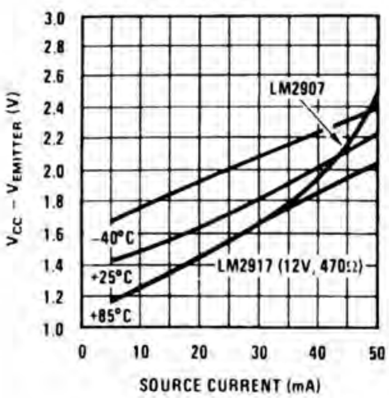
00794248

Tachometer Input Hysteresis vs Temperature



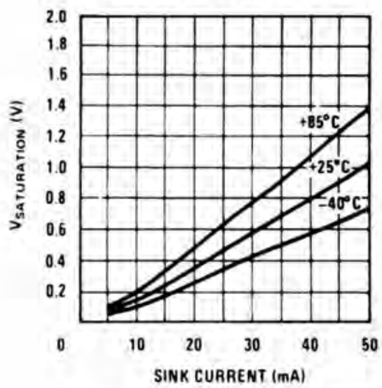
00794249

Op Amp Output Transistor Characteristics



00794250

Op Amp Output Transistor Characteristics



00794251

Applications Information

The LM2907 series of tachometer circuits is designed for minimum external part count applications and maximum versatility. In order to fully exploit its features and advantages let's examine its theory of operation. The first stage of operation is a differential amplifier driving a positive feedback flip-flop circuit. The input threshold voltage is the amount of differential input voltage at which the output of this stage changes state. Two options (LM2907-8, LM2917-8) have one input internally grounded so that an input signal must swing above and below ground and exceed the input thresholds to produce an output. This is offered specifically for magnetic variable reluctance pickups which typically provide a single-ended ac output. This single input is also fully protected against voltage swings to ±28V, which are easily attained with these types of pickups.

The differential input options (LM2907, LM2917) give the user the option of setting his own input switching level and still have the hysteresis around that level for excellent noise rejection in any application. Of course in order to allow the inputs to attain common-mode voltages above ground, input protection is removed and neither input should be taken outside the limits of the supply voltage being used. It is very important that an input not go below ground without some resistance in its lead to limit the current that will then flow in the epi-substrate diode.

Following the input stage is the charge pump where the input frequency is converted to a dc voltage. To do this requires one timing capacitor, one output resistor, and an integrating or filter capacitor. When the input stage changes state (due to a suitable zero crossing or differential voltage on the input) the timing capacitor is either charged or discharged linearly between two voltages whose difference is $V_{CC}/2$. Then in one half cycle of the input frequency or a time equal to 1/2 f_{IN} the change in charge on the timing capacitor is equal to $V_{CC}/2 \times C1$. The average amount of current pumped into or out of the capacitor then is:

$$\frac{\Delta Q}{T} = i_{c(AVG)} = C1 \times \frac{V_{CC}}{2} \times (2f_{IN}) = V_{CC} \times f_{IN} \times C1$$

The output circuit mirrors this current very accurately into the load resistor R1, connected to ground, such that if the pulses of current are integrated with a filter capacitor, then $V_O = i_c \times R1$, and the total conversion equation becomes:

$$V_O = V_{CC} \times f_{IN} \times C1 \times R1 \times K$$

Where K is the gain constant—typically 1.0.

The size of C2 is dependent only on the amount of ripple voltage allowable and the required response time.

CHOOSING R1 AND C1

There are some limitations on the choice of R1 and C1 which should be considered for optimum performance. The timing capacitor also provides internal compensation for the charge pump and should be kept larger than 500 pF for very accurate operation. Smaller values can cause an error current on R1, especially at low temperatures. Several considerations must be met when choosing R1. The output current at pin 3 is internally fixed and therefore $V_O/R1$ must be less than or equal to this value. If R1 is too large, it can become a significant fraction of the output impedance at pin 3 which degrades linearity. Also output ripple voltage must be considered and the size of C2 is affected by R1. An expression that describes the ripple content on pin 3 for a single R1C2 combination is:

$$V_{RIPPLE} = \frac{V_{CC}}{2} \times \frac{C1}{C2} \times \left(1 - \frac{V_{CC} \times f_{IN} \times C1}{I_2}\right) \text{pk-pk}$$

It appears R1 can be chosen independent of ripple, however response time, or the time it takes V_{OUT} to stabilize at a new voltage increases as the size of C2 increases, so a compromise between ripple, response time, and linearity must be chosen carefully.

As a final consideration, the maximum attainable input frequency is determined by V_{CC}, C1 and I_2:

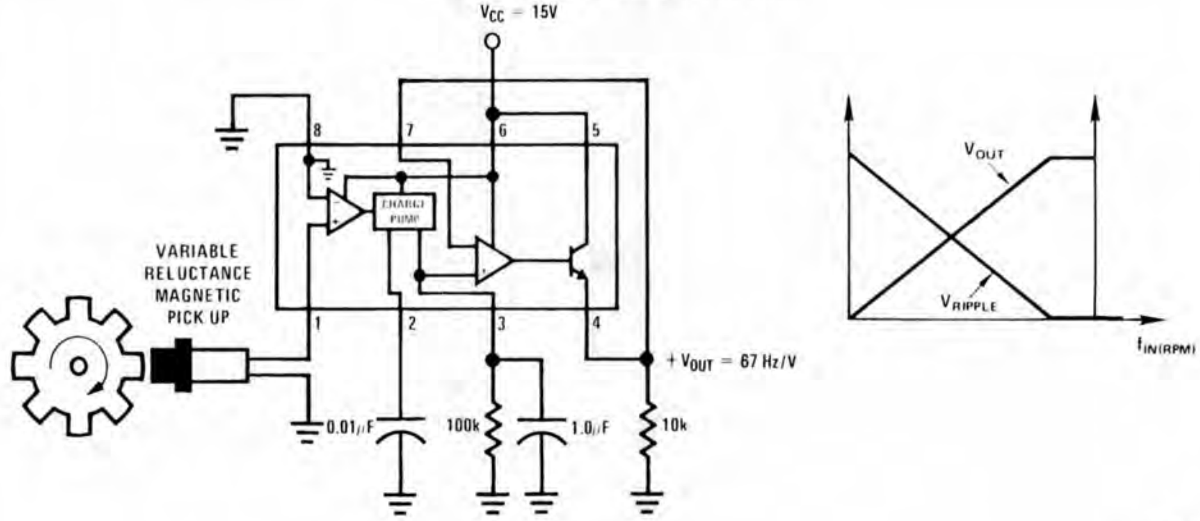
$$f_{MAX} = \frac{I_2}{C1 \times V_{CC}}$$

USING ZENER REGULATED OPTIONS (LM2917)

For those applications where an output voltage or current must be obtained independent of supply voltage variations, the LM2917 is offered. The most important consideration in choosing a dropping resistor from the unregulated supply to the device is that the tachometer and op amp circuitry alone require about 3 mA at the voltage level provided by the zener. At low supply voltages there must be some current flowing in the resistor above the 3 mA circuit current to operate the regulator. As an example, if the raw supply varies from 9V to 16V, a resistance of 470Ω will minimize the zener voltage variation to 160 mV. If the resistance goes under 400Ω or over 600Ω the zener variation quickly rises above 200 mV for the same input variation.

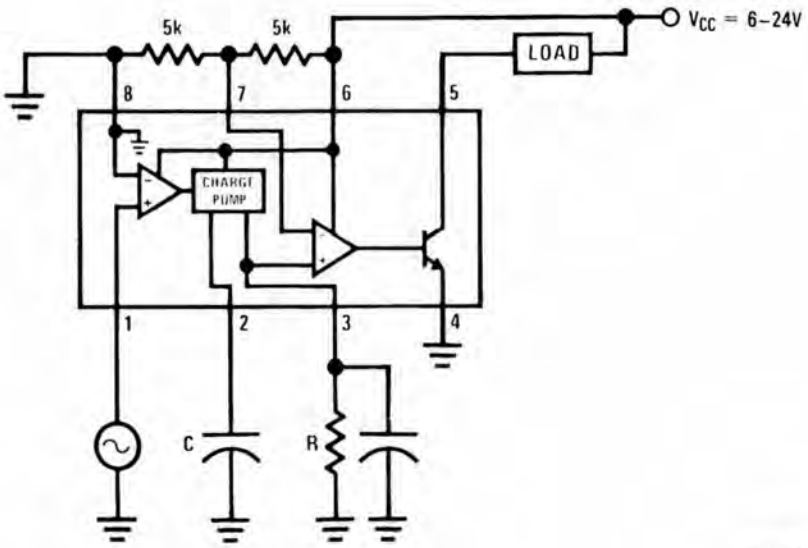
Typical Applications

Minimum Component Tachometer



00794208

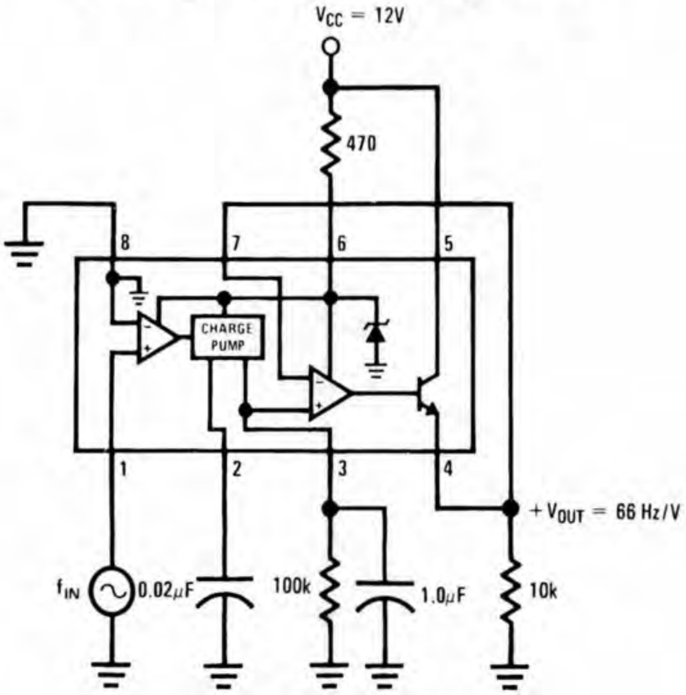
"Speed Switch" Load is Energized When $f_{IN} \geq \frac{1}{2RC}$



00794209

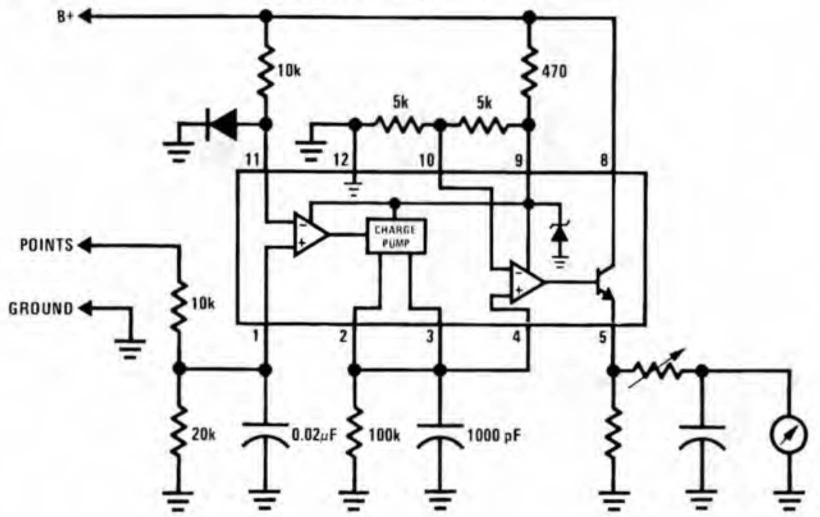
Typical Applications (Continued)

Zener Regulated Frequency to Voltage Converter



00794210

Breaker Point Dwell Meter



00794211

A.4

Poster