# MODELING AND OPERATION OF CENTRIFUGAL CASTING MACHINES FOR DUCTILE CAST IRON PIPES

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## ABSTRACT

Centrifugal casting machines are a production machines used to produce ductile cast iron pipes in the casting method in El Nasr Casting Company. The Casting Machines were manufactured by Thyssen Rheinstahl Technik GmbH [1]. They are driven by separately excited DC motor of a nominal voltage of 400V and nominal power 222 kW. Lower overall efficiency leads to higher electricity consumption. A brief background on the centrifugal casting process is presented along with typical casting machine electrical drive performance requirements. Motor performance characteristics and control strategies are described for both AC and DC machines. A case study is presented, where simulated measurements were performed on Centrifugal casting machine driven by a DC motor (222 kw) and replaced by AC motor (315 kw). Electrical energy, demand, and cost savings are analyzed.

The paper illustrates the difficulties that have been encountered of using DC drives, and presents a study of utilizing AC motor with its variable speed drive. The results indicate the simulated process performance in case of using AC motor.

The centrifugal casting machine driven by a AC motor requires less power to operate than the DC drive. On the average AC drive approximately draws 250 A and 60 kw, while the DC drive approximately draws 350 A and 64 kw. The final results are Electrical energy savings 7% and cost savings 10126 LE/yr for one machine.

## 1- INTRODUCTION

The Centrifugal Casting Machine shown in Figs. (2, 3 and 4) this is a production machine used to produce iron pipes using circular steel mould casting method. The machine functioning according to (De-Lavaud process) requires that a constant iron quantity per time unit is fed into the mould at constant traveling speed of the mould carriage and a constant number of mould revolutions in the mould. The molten iron is fed over the pouring runner to the rotating mold and pressed against the mould wall by centrifugal force. The mold is cooled by means of water flowing through the water bath in the mold carriage housing. The molten iron is abruptly cooled so that it solidifies quickly. Further fast cooling down, the solidified pipe and loosens from the mould wall as it shrinks so that the finished pipe can be drawn out after an appropriate cooling period. An inductive flow meter installed in the forward line is used to measure the through flow quantities. The mold is driven by direct current motor with DC drive contains SIMOREG (a converter units provide a variable DC voltage from the three-phase system suitable for supplying separately excited DC motors) and SITOR unit (containing several diodes and thyristors), regulated over vee belt pulleys and a poly-ribbed vee belt. The Hydraulic drives which move along with the mold carriage is supplied with Hydraulic oil from a central Hydraulic unit. It is synchronously pass along with the way of the mold carriage by a carrier arm flanged to the mold carriage, and rolls up on a frame. The drive cylinder is housed in the machine frame and supported by means of a cross beam. The drive cylinder is designed for a pressure of 160 bar at a maximum driving distance of 6100 mm. There are end point

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dampings on both sides. The damping at the piston rod side is a floating damping.

The travel way of the mold carriage and the mold revolution speed are controlled depending on the way length, by the so-called size-control carriage. It is positioned beside the mold carriage on a rail at the right side, opposite from the energy supply described above. The size-control carriage is taken along by the mold carriage by a carrier arm and a connecting rod. The longitudinal movement of the carriage is transformed into a rotary movement by rack and pinion, and by a rotary impulse sender it is entered into the machine control unit as electrical impulse.

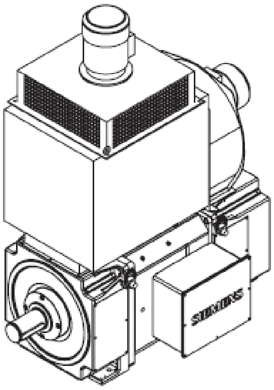

**Fig.1a- DC Motor 1HQ5**

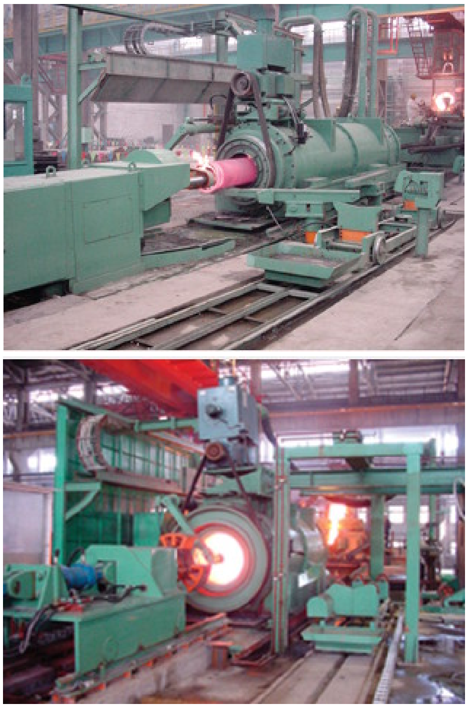

**Fig.1b - Centrifugal Casting Machine Assembly Production Line [1]**

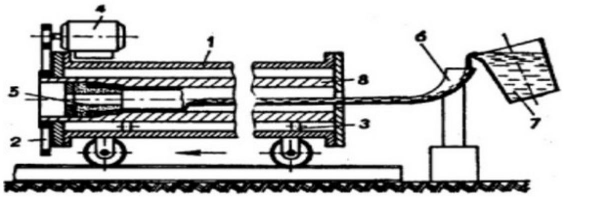

**Fig. 2- Centrifugal Casting Machine Components [1]**

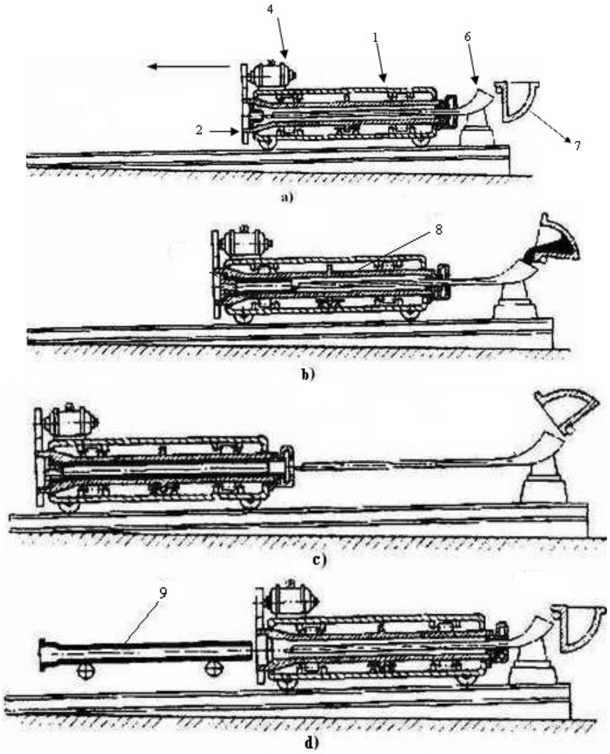

**Fig. 3- Centrifugal Casting Machine Process Description [1]**

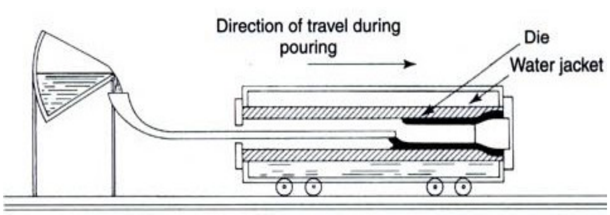


**Fig. 4- Essentials of De - Lavaud Pipe Casting Machine [1]**

## 1-1- MACHINE COMPONENTS [1]:

The machine components as shown in figures (2 and 3) are as follows:

### 1-1-1- Pouring Station

The Pouring station consists of pouring device (7) and the runners device (6):

#### 1-1-1-1-The Pouring Device (7)

The pouring device is tilted by means of a regulated direct current motor; the tilting process of the pouring device is controlled by means of a tacho-machine, an operating unit, and photo-captor.

### 1-1-1-2- The runner device (6)

The specially shaped runner, made of steel, which are adapted to the flowing behavior of the liquid iron. The runner supported rotating by way of one hydraulic swiveling drive. The runner can be twisted by $180^0$ and thereby allows the automatic emptying of iron remaining in the runner into the machine pit.

### 1-1-2- Casting Line

The Casting line consists of machine frame, drive cylinder, mould carriage (1) (The mould carriage carries all the devices for supporting, cooling, sealing and driving the mould), mould drive (The mould driven by a direct current motor (4), regulated over vee belt pulleys and a poly-v-ribbed vee belt (2)), core setting device and energy supply.

### 1.1.3 Pipe Drawing Line

The drawing carriage machine frame is designed as a sectional steel welded construction. The drawing carriage drive is positioned at the back end on the machine frame. The drive itself consists of a controllable direct current motor; the longitudinal movement of the drawing carriage is effected by a chain drive. The tongs are mounted movable on the machine frame; it carries the tongs for pulling the pipes. The longitudinal movement of the drawing carriage is transformed into a rotary movement by rack and pinion, and by a rotary impulse sender it is entered into the machine control unit as electrical impulse.

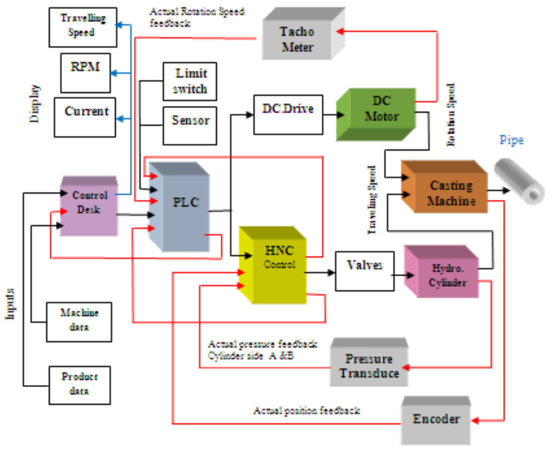


**Fig. 5- Block Diagram of Process Description Control**

### 1-2- THE FACTORS AFFECTING ON THE WALL THICKNESS OF THE PIPE [1]:

The factors affecting the wall thickness of the pipe are:

### 1-2-1- Pouring Pot Tilting Speed (Iron Quantity per Time Unit)

Tilting by hydraulic motor (7)

### 1-2-2-Mould Rotating Speed

Rotation by DC motor no. (4)

### 1-2-3- Traveling Speed of Mould Carriage (1)

Moving by Hydraulic Cylinder, the drive cylinder is designed for a pressure of 160 bars at a maximum driving distance of 6100 mm. there are end point damping on both sides. The damping at the piston rod side is a floating damping.

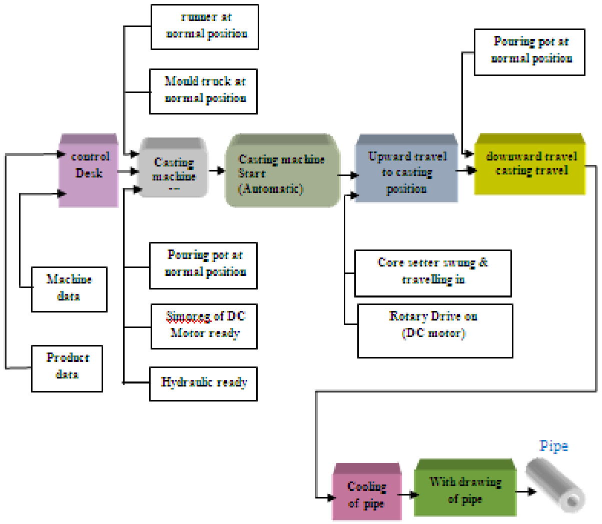


**Fig. 6- Block Diagram of Process Steps**

## 2- PROCESS DESCRIPTION

The process description as shown in figure 3 (a, b, c and d) and figure 4. The pouring pot (7) (is filled with liquid iron from the casting ladle up to the overflow. At the same time the core setting device is equipped with a socket core and the socket area of the mold is charged with scatter material. After the start release is given by the pouring desk and the control desk, the core setter swings in and presses the core against the core position of the mold. At the same time the mold drive motor (4) starts and the revolution speed ramp increase from 0 to 450 rpm from time 0 to 15 seconds Fig. 7 the mold carriage begins the upward travel fig. (3a), the travelling speed ramp increase from 0 to 300 mm/s from time 0 to 5 seconds Fig. 8 while the scattering device is in operation. Before the uphill position is reached, the pouring pot starts tilting fig.(3b), the injection device charges inoculants, and the slag-free iron runs into the runner inlet and into the runner (6). As soon as the iron flowing through the mold (8) has filled the socket while the mold carriage (1) is standing, the mold carriage begins the casting travel at constant revolution speed 450 rpm until time 70 seconds Fig. (7) and constant travelling speed of mold carriage 300 mm/s until time 70 seconds Fig. 8. During the casting travel, the injection device feeds inoculants before the iron jet into the mold. At the end of the pouring pot tilting period, which depends on the nominal diameter, the pot tilts back fig. (3d), and the injection device is switched off. As the iron jet becomes continuously weaker, the mold carriage traveling speed becomes correspondingly slower 10 mm/s Fig. 8, while the number of mold revolutions increases to 500 rpm until time 85 seconds Fig. 7.

When the rest of the iron has flown into the mold at the spigot end, the scattering device is switched off, and the mold carriage goes downhill at increased speed to 300 mm/s Fig.8. The mold revolution speed is reduced to the cooling speed 350 rpm Fig.7. At the end of the cooling period, which depends on the nominal diameter DN1000, the core setting device swings out, and the pipe can be drawn out. The drawing and rolling off of the pipe (9) from the drawing line are carried out automatically [1].

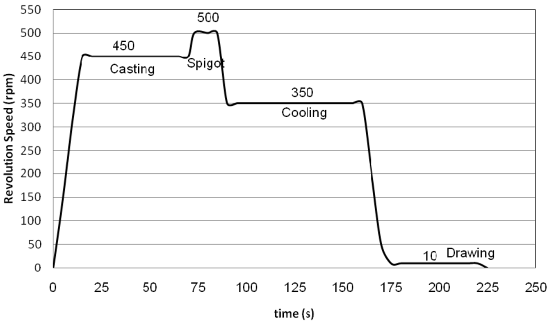


**Fig. 7-Practical Revolution speed vs. casting time for DN1000 along pipe length[1]**

# 3- MACHINE PERFORMANCE DATA

## 3-1- Revaluations Speed

**Table 1- Casting Revolution Speed Values for Pipe Size DN 1000 [1]**

| DN (mm) | 1000 |
|---|---|
| Casting speed(rpm) | 450 |
| Spigot end (rpm) | 500 |
| Cooling speed (rpm) | 350 |
| Drawing speed (rpm) | 10 |

From time 0 to 15 seconds The revolution speed ramp increase from 0 to 450 rpm (casting speed of ductile iron pipe shaft DN1000), this speed is constant until time 70 seconds, then The revolution speed ramp increase from 450 to 500 rpm (casting speed of ductile iron pipe spigot DN 1000), this speed is constant until time 85 seconds, the speed ramp lowered to 350 rpm (cooling speed of ductile iron pipe DN1000), this speed is constant until time 175 seconds, the speed ramp lowered to 10 rpm (drawing speed of ductile iron pipe DN1000), this speed is constant until time 225 seconds and the speed ramp lowered to 0 rpm.

## 3-2- Traveling Speed

**Table 2- Casting Traveling Speed Values for Pipe Size DN1000 [1]**

| DN | 1000 |
|---|---|
| Travelling Casting speed (m/s) | 0.3 |
| Creeping speed (m/s) | 0.1 |
| Spigot end (m/s) | 0.3 |
| Cooling speed (m/s) | 0 |
| Drawing speed (m/s) | 0 |

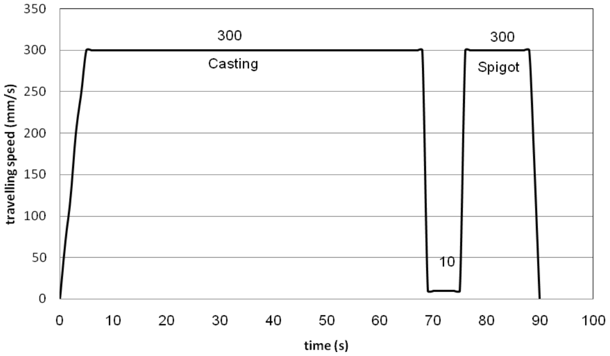


**Fig. 8- Practical Travelling Speed vs. Casting Time for DN1000 Along Pipe Length (Thyssen Rheinstahl Technik GmbH Documentations)**

From time 0 to 5 seconds The travelling speed ramp increase from 0 to 300 mm/s, (travelling speed of ductile iron pipe shaft DN1000), this speed is constant until time 70 seconds, the speed ramp lowered to 10 mm/s (creeping speed) and this speed is constant until time 75 seconds, then the speed ramp increase to 300 mm/s (travelling speed of ductile iron pipe spigot DN1000), this speed is constant until time 85 seconds, and the speed ramp lowered to 0 mm/s.

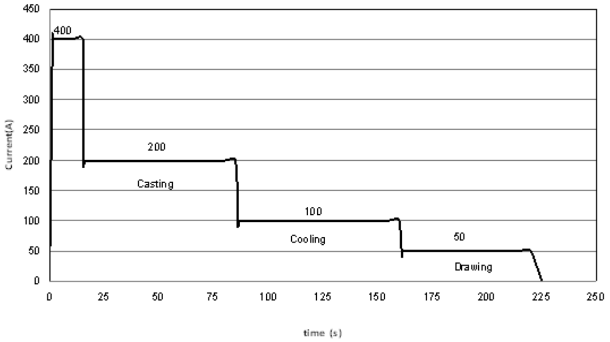


**Fig. 9- Practical Current vs. Casting Time for DN1000 Along Pipe Length (Thyssen Rheinstahl Technik GmbH Documentations)**

The current ramp increases from 0 to 400 A (starting current), this current is constant until 15 seconds**,** the current ramp lowered to **200 A (**casting of ductile iron pipe shaft and spigot DN 1000), this current is constant until time 85 seconds, then the current ramp lowered to **100 A** (cooling of ductile iron pipe DN1000) , this current is constant until time 160 seconds, the current ramp lowered to 50 A (drawing of ductile iron pipe DN1000), this current is constant until time 225 seconds and the current ramp lowered to 0 A.

## 4- DETERMINATION OF INERTIA

### 4-1- Pipe Specimen

The practical data collected during production of iron pipe DN 1000 by Centrifugal casting machine**.** The material specifications and dimensions of the pipe are detailed in the following [1].

### 4.1.1 Material Specifications of the Pipe

The ductile iron pipes with nominal diameter DN 100 to DN 1000 mm and standard length 6000 mm have a round cross section confirming to the dimensional and weight requirements of (DIN 28610-ISO2531/1986(E)). The iron pipes produced were seamless of cast iron in Centrifugal casting machine. After casting which the iron pipes may be subjected to a suitable heat treatment at $950^0$ C-$250^0$ C in heat treatment furnace for 45 minutes (DIN 28610-ISO 2531/1986(E)) in order to give them the required mechanical characteristic. The material chemical analysis was carried out at EL NASR CASTING COMPANY by spectrometer (metal analysis) ARL 3460 [1].

### 4-1-2- Pipe Chemical Analysis

The chemical analysis for the pipe samples gave the following results:

| C% | Si% | P% | Mn% | Mg% | S% | Cu% |
|---|---|---|---|---|---|---|
| 3.2-3.6 | 2.2-2.8 | 0.005-0.04 | 0.1-0.5 | 0.03-0.05 | 0.005-0.02 | <0.40 |

### 4-1-3- Pipe Dimensions

Pipes diameters and thickness were according to (DIN 28610- ISO 2531/1986(E)) Class K9.The pipes have 1048 ± 0.1mm outer diameter with 13.5 ± 0.1 mm thickness and 6200 ± 30 mm length; as shown in Fig. 10 and table 3.

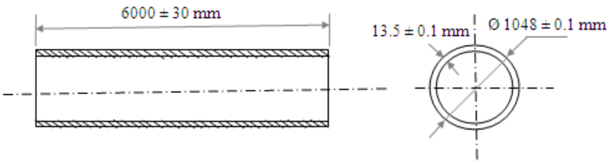


**Fig. 10-Pipe Dimension**
**(Thyssen Rheinstahl Technik GmbH Documentations)**

**Table 3- Ductile Iron Pipe Specification DN1000 [1]**
**(DIN 28610 - ISO 2531/1986(E)) Class K9**

| | |
|---|---|
| **Outer diameter (mm)** | **1048 ± 0.1** |
| **inner diameter (mm)** | **1048 ± 0.1** |
| **Material** | **Ductile cast iron** |
| **Density (kg/m$^3$)** | **7200** |
| **Length (mm)** | **6000 ± 30** |
| **Total mass (kg)** | **2267** |

### 4-2-Pipe Inertia ($J_1$)

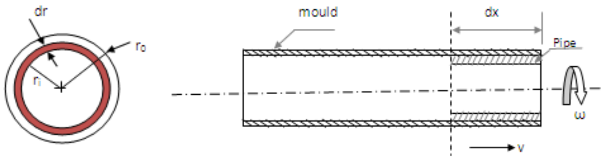


**Fig. 11- Ductile Iron Pipe Dimension**
**(Thyssen Rheinstahl Technik GmbH Documentations)**

$$\because \quad dJ_1 = r^2\, dm$$

$$dJ_1 = r^2 (2\pi r \rho\, dx\, dr)$$

$$= 2\pi r^3 \rho\, dx\, dr$$

$$\therefore \quad \frac{dJ_1}{dt} = 2\pi r^3 \rho \frac{dx}{dt} dr$$

$$v = \frac{dx}{dt} \quad travelling\ speed\ of\ mould$$

$$\therefore \quad \frac{dJ_1}{dt} = 2\pi r^3 \rho v\, dr$$

$$dJ_1 = 2\pi r^3 \rho v\, dr\, dt$$

$$J_1 = \rho \pi d s v t$$

$$J_1 = \pi * (7200) * (0.3) * 1.048 * 0.0135 * t = 96t \quad \textbf{... (1)}$$

### 4-3- Mould Inertia $J_0$

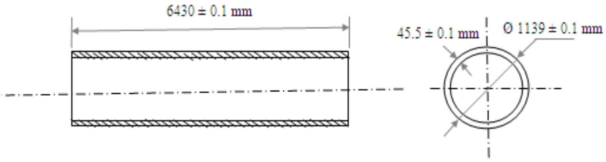


**Fig.12- Mould Dimensions**
**(Thyssen Rheinstahl Technik GmbH Documentations)**

### 4-3-1- Mould Specifications

The mould, which is made of special grade steel, is taken up and supported at the socket side by the antifriction bearing head and at the spigot end side the mould is supported by mould support rollers [1].

**Table 4-Mould Specification [1]**

| | |
|---|---|
| **Outer diameter (mm)** | **1139** |
| **Inter diameter (mm)** | **1048** |
| **Material** | **Alloy steel** |
| **Density (kg/m$^3$)** | **7800** |
| **Length (mm)** | **6430** |

$$J_0 = \frac{\pi}{32}\rho L(d_0^4 - d_i^4)$$

$$J_o = \frac{\pi}{32}(7800)(6.430)((1.139)^4 - (1.048)^4) = 2347.5 kg/m^3 \quad \ldots\ldots\ldots (2)$$

### 4-4- Motor Inertia [1]$J_m$

$J_m = 7.5$ kg/m$^3$ ………..……………….. (3)

From (1, 2 and 3)

$$J = J_0 + J_1 + J_m$$

J = 96t + 2347.5 + 7.5

J = 2355 + 96t ………………...………………… (4)

### 4-5-Technical Data of DC Motor Type: Siemens 1HQ5-312-5GE40-6JU3-Z Separately Excited

**Table 5-Technical Data of DC Motor Siemens 1HQ5-312-5GE40-6JU3-Z**

| | |
|---|---|
| **Supply voltage V (AC)** | **380 v** |
| **Supply frequency (Hz)** | **50** |
| **Rated armature voltage $V_a$ (DC)** | **400 v** |
| **Rated speed $N_N$ (rpm)** | **1130** |
| **Rated Output $P_N$ (KW)** | **222** |
| **Rated Torque $T_N$ (Nm)** | **1880** |
| **Max. field weakening Speed $N_F$ (rpm)** | **2100** |
| **Rated current $I_N$ (A)** | **590** |
| **Armature Resistance At $120^0$ $R_a$ (m Ω)** | **26.2** |
| **Armature inductance $L_a$ (mH)** | **0.25** |
| **Motor Moment of inertia J (kgm²)** | **7.50** |
| **Rated field voltage $V_F$ (v)** | **310** |
| **Field power $P_F$ (KW)** | **1.7** |
| **Efficiency η%** | **93** |

## 5-DC MOTOR EQUATIONS

The input voltage may be applied to the field or armature terminals. The air-gap flux ? of the motor is proportional to the field current, provided the field is unsaturated [2], so that

$$\phi = K_f i_f(t) \quad \ldots\ldots\ldots (5)$$

The torque developed by the motor is assumed to be related linearly to ? and the Armature current as follows:

$$T_m = K_1 \phi i_a(t) = K_1 K_f i_f(t) i_a(t) \quad \ldots\ldots\ldots (6)$$

To have a linear system, one current must be maintained constant while the other current becomes the input current.

### 5-1- DC Motor, Armature -Controlled, Rotational Actuator [2]

The armature-controlled DC motor uses the armature current $i_a$ as the control variable, ($i_f$ = const, $i_a$= input)

$$T_m = (K_1 K_f i_f) i_a(t) = K_m i_a(t) \quad \ldots\ldots\ldots (7)$$

The armature current is related to the input voltage applied to the armature by

$$V_a = R_a i_a(t) + L_a \frac{di_a}{dt} + V_b \quad \ldots\ldots\ldots (8)$$

The back electromotive - force voltage proportional to the motor speed. Therefore,

$$V_b = K_b \omega \quad \ldots\ldots\ldots (9)$$

From equation (8), (9)

$$V_a = R_a i_a(t) + L_a \frac{di_a}{dt} + K_b \omega$$

$$\frac{di_a}{dt} = \frac{1}{L_a}(V_a - R_a i_a(t) - K_b \omega) \quad \ldots\ldots\ldots (10)$$

The motor torque Tm is equal to the torque delivered to the load. This relation may be expressed as:

$$T_m = T_L + T_d \quad \ldots\ldots\ldots (11)$$

The load torque for rotating inertia,

$$T_L = \frac{d}{dt}(J\omega) + B\omega \quad \ldots\ldots\ldots (12)$$

$$T_L = \omega \frac{dJ}{dt} + J \frac{d\omega}{dt} + B\omega \quad \ldots\ldots\ldots (13)$$

$$J = J_L + J_m \quad \ldots\ldots\ldots (14)$$

$$J_L = J_0 + J_1 \quad \ldots\ldots\ldots (15)$$

$$\therefore \quad J = J_0 + J_1 + J_m \quad \ldots\ldots\ldots (16)$$

From equations (13), (16):

$$T_L = \omega \frac{d}{dt}(J_0 + J_1 + J_m) + (J_0 + J_1 + J_m) \frac{d\omega}{dt} + B\omega$$

$$T_L = \omega\left(\frac{dJ_0}{dt} + \frac{dJ_m}{dt} + \frac{dJ_1}{dt}\right) + (J_0 + J_m) \frac{d\omega}{dt} + J_1 \frac{d\omega}{dt} + B\omega$$

$$T_L = \omega\left(0 + 0 + \frac{dJ_1}{dt}\right) + (J_0 + J_m + J_1) \frac{d\omega}{dt} + B\omega$$

$$T_L = \omega \frac{dJ_1}{dt} + (J_0 + J_m + J_1) \frac{d\omega}{dt} + B\omega \quad \ldots (17)$$

$$T_L = (J_0 + J_m + J_1) \frac{d\omega}{dt} + B\omega \quad \ldots\ldots\ldots (18)$$

$$\frac{d\omega}{dt} = \frac{1}{(J_0 + J_m + J)}(K_m i_a(t) - B\omega) \quad \ldots\ldots\ldots (19)$$

From equations (10), (19):

$$\frac{d}{dt}\begin{bmatrix} i_a \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{-R_a}{L_a} & \frac{-K_b}{L_a} \\ \frac{K_m}{J_0+J_m+J_1} & \frac{-B}{J_0+J_m+J_1} \end{bmatrix} \begin{bmatrix} i_a \\ \omega \end{bmatrix} + \begin{bmatrix} \frac{1}{L_a} \\ 0 \end{bmatrix} V_a$$

…………………………………………….………. (20)

$$\omega(t) = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ \omega \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix} V_a \quad \text{…………………...} \quad (21)$$

**Table 6- DC Motor (1HQ5-312-5 GE40-6JU3-Z) Parameters**

| | |
|---|---|
| **Back - emf constant Kb (volt/rad s)** | **3.25** |
| **Motor constant Km (Nm/A)** | **3.19** |
| **Viscous friction (Nm/rad s)** | **15.88** |

From table 6 and equations (4), (20):

$$\frac{d}{dt}\begin{bmatrix} i_a \\ \omega \end{bmatrix} = \begin{bmatrix} -104.8 & -13000 \\ \frac{3.19}{2355+96t} & \frac{-15.88}{2355+96t} \end{bmatrix} \begin{bmatrix} i_a \\ \omega \end{bmatrix} + \begin{bmatrix} -4000 \\ 0 \end{bmatrix} V_a$$

$$\omega(t) = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_a \\ \omega \end{bmatrix} + \begin{bmatrix} 0 \end{bmatrix} V_a$$

From equation (4), (19):

$$\frac{d\omega}{dt} = \frac{1}{(2355+96t)}(K_m\ i_a(t) - B\omega)$$

Solution of differential equation

$$\frac{d\omega}{dt} + \frac{1}{(2355+96t)} B\omega = \frac{1}{(2355+96t)} K_m\ i_a(t)$$

This equation as general form,

y' + p(x) y = Q(x) [3]

General solution:

$$y = e^{-\int p(x)\,dx}\left[\int Q(x) e^{\int p(x)\,dx}\, dt + C\right] \quad [3]$$

$$p(x) = \frac{B}{(2355+96t)} = \frac{15.88}{(2355+96t)}$$

$$Q(x) = \frac{K_m\ i_a(t)}{(2355+96t)} = \frac{3.2\ i_a(t)}{(2355+96t)}$$

$$\omega = e^{-\int \frac{15.88}{(2355+96t)} dt}\left[\int \frac{3.2\ i_a(t)}{(2355+96t)} e^{\int \frac{15.88}{(2355+96t)} dt}\, dt + C\right]$$

$$\omega = 0.03 i_a + \frac{C}{(2355+96t)^{0.16}} \quad \text{………….. (22)}$$

Initial conditions

at t = $t_0$, $i_a = i_0$, $\omega = \omega_0$

$$C = (2355+96t_0)^{0.16}(\omega_0 - 0.03 i_0)$$

$$\omega = 0.03 i_a + \left(\frac{2355+96t_0}{2355+96t}\right)^{0.16}(\omega_0 - 0.03\ i_0) \quad \text{… (23)}$$

$$P_{in} = V_a I_a + I_f V_f \quad KW$$

$$P_{in} = V_a I_a + 1.7 \quad KW$$

$$\eta = \frac{P_{out}}{P_{in}}\ 100\ \%$$

$$P_{out} = T * \omega$$

$$T = \frac{P_{out}}{\omega} \quad \text{Nm}$$

From equation (20):

$$\frac{di_a}{dt} = \frac{1}{L_a}(V_a - R_a i_a(t) - K_b\omega)$$

Solution of differential equation

$$\frac{di_a}{dt} + \frac{R_a}{L_a} i_a(t) = \frac{1}{L_a}(V_a - K_b\omega)$$

This equation as general form,

y' + p(x) y = Q(x) [3]

General Solution:

$$y = e^{-\int p(x)\,dx}\left[\int Q(x) e^{\int p(x)\,dx}\, dt + C\right] \quad [3]$$

$$p(x) = \frac{R_a}{L_a}$$

$$Q(x) = \frac{1}{L_a}(V_a - K_b\omega)$$

$$i_a = \frac{(V_a - K_b\omega)}{R_a} + C\ e^{-\frac{R_a}{L_a}t}$$

Initial Conditions

at t = $t_0$ , $i_a = i_0$ , $\omega = \omega_0$ , $V_a = V_0$

$$C = e^{\frac{R_a}{L_a}t_0}\left(i_{a0} - \frac{(V_{a0} - K_b\omega_0)}{R_a}\right)$$

$$V_a = R_a\left(i_a - e^{\frac{R_a}{L_a}(t_0 - t)}\left(i_{a0} - \frac{(V_{a0} - K_b\omega_0)}{R_a}\right)\right) + K_b\omega$$

$$V_a = 26.2*10^{-3}\left(i_a - e^{105(t_0 - t)}\left(i_{a0} - \frac{(V_{a0} - 3.2\omega_0)}{R_a}\right)\right) + 3.2\omega \quad (24)$$

## 6 - AC INDUCTION MOTOR (THREE PHASE)

**TABLE 7- AC Motor (Induction Motors) Self Ventilated Technical Data**

| P (kw) | N rpm | T Nm | η % | Cos θ | I A | J $Kgm^2$ | $N_s$ rpm | pole | R ohm | X ohm | type |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 315 | 1488 | 2022 | 95 | 0.86 | 560 | 5 | 1500 | 4 | 5.7e-3 | 3.4e-3 | 1LG6312-4MA1 |

### 6-1- Electrical Torque produced by IM:

$$T \,\alpha\, \phi I \cos\theta$$

$$T = K \phi I \cos\theta \quad \text{………… ………………..} \quad (25)$$

$$\phi \,\alpha\, E_1$$

$$K = \frac{E_2}{E_1}$$

$$I = \frac{SE_2}{Z_2}$$

$$Z_2 = \sqrt{R^2 + (SX)^2}$$

$$I = \frac{SE_2}{\sqrt{R^2 + (SX)^2}}$$

$$\cos\theta = \frac{R}{Z_2} = \frac{R}{\sqrt{R^2 + (SX)^2}}$$

From equation (25):

$$T = KE_2 \frac{SE_2}{\sqrt{R^2 + (SX)^2}} \; \frac{R}{\sqrt{R^2 + (SX)^2}}$$

$$T = KSE_2^2 \; \frac{R}{R^2 + (SX)^2}$$

$$K = \frac{3}{2\pi n_s}$$

$$T = (\frac{3}{2\pi n_s})(SE_2^2) \; \frac{R}{R^2 + (SX)^2} \quad \text{…………} \quad (26)$$

### 6-2- Mechanical Torque produced

The motor torque T is equal to the torque delivered to the load. This relation may be expressed as:

$$T = T_L + T_d$$

at Td = 0

$$T = T_L$$

From equation (18), (26):

$$(\frac{3}{2\pi n_s})(SE_2^2) \frac{R}{R^2 + (SX)^2} = (J_0 + J_m + J_1) \frac{d\omega}{dt} + B\omega$$

$$J_1 = \rho \pi d\, sv\, t$$

$$J_1 = \pi*(7200)*(0.3)*1.048*0.0135*t = 96\ t$$

$$\frac{d\omega}{dt} = \frac{1}{(J_0 + J_m + J_1)} [(\frac{3}{2\pi n_s})\ (SE_2^2)\ \frac{R}{R^2 + (SX)^2} - B\omega]$$

$$\frac{d\omega}{dt} + \frac{B}{(J_0 + J_m + J_1)}\ \omega = \frac{1}{(J_0 + J_m + J_1)} (\frac{3}{2\pi n_s})(SE_2^2)\ \frac{R}{R^2 + (SX)^2}$$

This equation as general form,

y' + p(x) y = Q(x) [3]

General Solution:

$$y = e^{-\int p(x)\,dx} \left[ \int Q(x)\, e^{\int p(x)\,dx}\ dt + C \right] \quad [3]$$

$$p(x) = \frac{B}{(J_0 + J_m + J_1)}$$

$$Q(x) = \frac{1}{(J_0 + J_m + J_1)} (\frac{3}{2\pi n_s})(SE_2^2)\ \frac{R}{R^2 + (SX)^2}$$

$$\omega = e^{-\int \frac{B}{(J_0 + J_m + J_1)} dt} \left[ \int \frac{\frac{1}{(J_0 + J_m + J_1)} (\frac{3}{2\pi n_s})(SE_2^2)}{\frac{R}{R^2 + (SX)^2}\, e^{\int \frac{B}{(J_0 + J_m + J_1)} dt}}\ dt + C \right]$$

$$\omega = e^{-\int \frac{B}{(2347.5 + J_m + 96t)} dt} \left[ \int \frac{\frac{1}{(2347.5 + J_m + 96t)} (\frac{3}{2\pi n_s})(SE_2^2)}{\frac{R}{R^2 + (SX)^2}\, e^{\int \frac{B}{(2347.5 + J_m + 96t)} dt}}\ dt + C \right]$$

$$\omega = \frac{1}{B} (\frac{3}{2\pi n_s})(SE_2^2)\ \frac{R}{R^2 + (SX)^2} + \frac{C}{(2347.5 + J_m + 96t)^{\frac{B}{96}}} \quad \text{…………..} \quad (27)$$

## Initial Conditions

at $t = t_0$ , $\omega = \omega_0$

$$C = (2347.5 + J_m + 96 t_o)^{\frac{B}{96}} (\omega_0 - \frac{1}{B}(\frac{3}{2\pi n_s})(SE_2^2) \frac{R}{R^2 + (SX)^2}$$

$$\omega = (\frac{0.19}{2\pi n_s})(SE_2^2) \frac{R}{R^2 + (SX)^2} + (\frac{(2355 + 96 t_o)}{(2355 + 96 t)})^{0.16} (\omega_0 - (\frac{0.19}{2\pi n_s})(SE_2^2) \frac{R}{R^2 + (SX)^2}) \quad \ldots. (28)$$

$$T = (\frac{3}{2\pi n_s})(SE_2^2) \frac{R}{R_2^2 + (SX_2^2)^2}$$

$$I = T \frac{\sqrt{R^2 + (SX)^2}}{RE_2} (\frac{2\pi n_s}{3}) \quad P_{in} = \sqrt{3} V I \cos\theta$$

$$P_{out} = T * \omega \quad OR \quad P_{out} = P_{in} * \eta \quad watt$$

## 7- RESULTS

The following results are achieved:

### 7-1- Comparison between: AC motor (315 kw, 1500 rpm) and DC motor (222 kw, 1500 rpm)

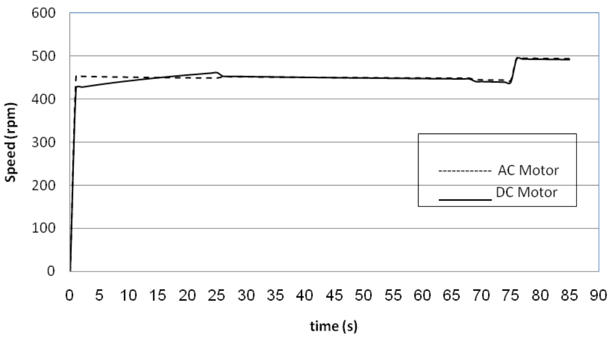


Fig. 13- Revolution Speed vs. Casting Time

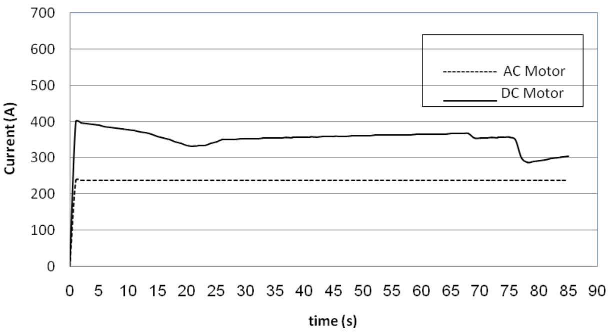


Fig. 14- Armature Current vs. Casting Time

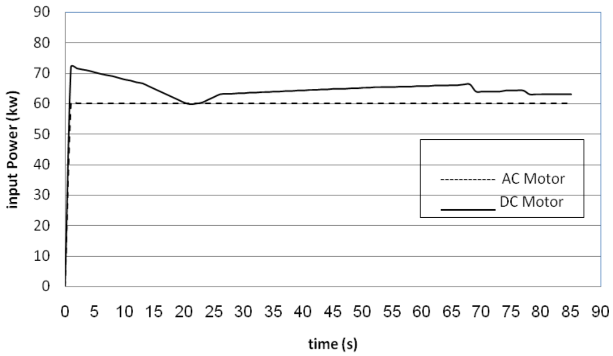


Fig. 15- Input power vs. Casting Time

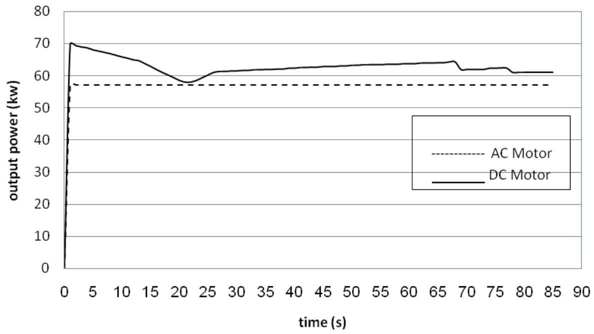


Fig. 16 - Output power vs. Casting Time

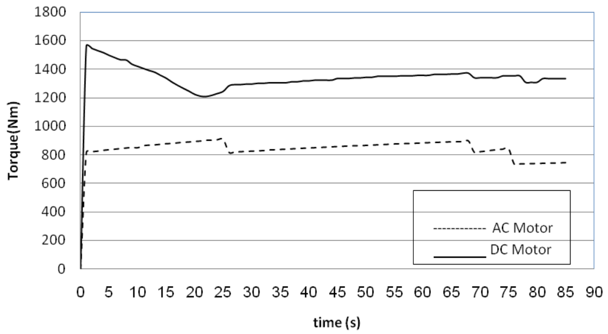


Fig. 17- Torque vs. Casting Tim

### 7-2- Energy Savings

Centrifugal casting machine driven by a DC drive system and replacement by an AC drive system theoretically. The AC retrofit resulted in a significant reduction in total electrical energy consumption as well as an increase in productivity. Detailed electrical measurements (instantaneous revolution speed and current measurements) where performed on one of the centrifugal casting machine powered by a DC system. The mathematically revolution speed, current drawn, input power, output power and torque for the AC and DC driven centrifugal casting machine for a period of 225 seconds (time of pipe DN1000 production) is presented in Figures 13,14,15,16 and 17.

Some interesting features shown in Figures 13,14,15,16 and 17 are:

The AC drive requires less current (thus less power) to operate than the DC drive for centrifugal casting machine. Since replacing the DC drive system with an AC drive system resulted in a productivity improvement, comparing the electrical energy consumption before and after the retrofit requires normalizing the energy consumption versus product rate (pipes/hour, ton/hr).

### 7-3- Anticipated Savings

The electrical energy savings will be calculated by comparing the electrical energy consumption of the DC driven with that of the AC driven centrifugal casting machine. Table 8 contains the products Specifications (DN1000) [1].

**Table 8- Casting Machine Products Specifications (DN1000)**

| | |
|---|---|
| **Max. machine capacity (pipe/hr)** | **16** |
| **Production time (sec/pipe)** | **225** |
| **Pipe weight (ton) - K9** | **2.267** |
| **Working days/month** | **25** |
| **Working shifts/days** | **3** |
| **Working hrs/shift** | **6** |

The annual amount of product processed, P, by a centrifugal casting machine can be calculated as follows [5]:

P = TP × H …………………………..………. (29)

The total amount of product, P, processed through the DC driven casting machine can be estimated as follows:

From table 8 and equation 29:

H = 3*6*25*12 = 5400 hr/yr

P = 16 * 5400 = 86400 pipe/yr …………. .(30)

Or

P = 16 *2.267* 5400 = 195868.8 ton/yr …… (31)

The energy intensity, EI, which is the average amount of energy required to process one pipe of ductile cast iron through a casting machine can be calculated as follows[5]:

EI = kW / TP ………………………………. (32)

From figure 15 (input power of DC and AC drive)

The average input power for DC driven casting machine 64 kw

The average input power for AC driven casting machine 60 kw

The energy intensity, EID, for DC driven casting machine can be calculated from equation 32 as follows:

EID = (64 kW) / (16 pipe/hr)

EID = 4 kWh/pipe

EID = 4/2.267 = 1.76 kWh/ton

The energy intensity, EIA, for the AC driven casting machine can be calculated from equation 32 as follows:

EIA = (60 kW) / (16 pipe/hr)

EIA = 3.75 kWh/pipe

EIA = 3.75/2.267 = 1.65 kWh/ton

The electrical energy savings, EES, can be calculated as follows

EES = P x (EID – EIA)……………………… (33)

The electrical energy savings, EES, for replacing the DC drive system with an AC drive system can be calculated as follows:

EES = (195868.8 ton/yr) (1.76 kWh/ton – 1.65 kWh/ton)

EES = 21545.5 kWh/yr

The electrical energy savings of 21545.5 kWh/yr for retrofitting the DC driven casting machine with an AC drive system would reduce the electrical energy consumption by approximately 7% over the existing DC drive system.

The estimated electrical energy cost savings, EECS, that can result from replacing the DC drive system with an AC driven system can be calculated as follows:

EECS = EES × (ave. electricity unit cost)

EECS = (21545.5 kWh/yr) (0.47 LE/kWh)

EECS = 10126 LE/yr (for one machine)

EECS = 5*10126 = 50631.9 LE/yr (for five machines)

## 8- CONCLUSION

Replacing of DC motor with AC motor in centrifugal casting machines offering the following: performance improvements as predicted from mathematical relations.

* Better control of motor speed, torque, and power
* Quick response to load changes
* Ability to provide max. torque at zero speeds

Since Replacing of DC motor with an AC motor in centrifugal casting machines, Due to higher energy efficiency of AC motors versus DC motors and the improved controls strategy (which allows centrifugal casting machines to run faster), AC drive system retrofits can result in a significant electrical energy saving and productivity improvement of centrifugal casting machines, by lowering the energy intensity (kWh/ton) of centrifugal casting machines. It is expected that an AC retrofit will result in an energy intensity reduction of approximately 7%. In the above case study, the AC retrofit of the centrifugal casting machines saved approximately 21545.5 kWh/yr, equivalent to 10126 LE/yr (for one machine), 50631.9LE/yr (for five motors). It is expected that an AC retrofit will result in an energy intensity reduction.

**9- NOMENCLATURE**

| | | |
|---|---|---|
| di | : | pipe inter diameter (m) |
| d0 | : | pipe outer diameter (m) |
| ρ | : | pipe density ( kg/m3 ) |
| t | : | casting time (s) |
| v | : | mould travelling speed (m/s) |
| L | : | mould length (m) |
| J | : | overall inertia |
| JL | : | load inertia |
| Jm | : | motor inertia |
| J0 | : | mould inertia |
| J1 | : | pipe inertia |
| B | : | overall viscous friction |
| Bm | : | motor viscous friction |
| BL | : | load viscous friction |
| if | : | the field current |
| ia | : | the armature current |
| Km | : | the motor constant |
| Kb | : | Back – emf constant |
| TL | : | the load torque |
| Td | : | the disturbance torque |
| ω | : | revolution speed |
| E1 | : | stator emf |
| E2 | : | rotor emf |
| K | : | transformation ratio |
| Φ | : | flux |
| Cos θ | : | power factor |
| ns | : | synchronous speed (rad/s) |
| SE2 | : | rotor induced emf |
| Z2 | : | total impedance |
| S | : | Slip |
| TP | : | pipe production, pipe/hr |
| H | : | operating hours, hr/yr |
| EI | : | energy intensity, |
| TP | : | pipe production, pipe/hr |
| Vb | : | back electromotive-force voltage |

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