ENERGY SAVING MECHANISM FOR PUMP'S DRIVE USING MATLAB PROGRAM

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In this work we use MATLAB program implementation for controlling to move of the pump's mechanical characteristics (H-Q) to the working zone (Ω-M) of induction motor by implementing a Variable Frequency Drives (VFD), in order to reduce the consumer energy (i.e. saving energy) and calculate the final amount of power fed by voltage source to induction motor. Our calculation shows that, we get a high benefit in cost, reliability improvements and reduce the power losses.

Keywords: Variable frequency drive, adjustable speed drive, energy saving, pump drive, a.c drive system.

1. Introduction

A variable frequency (speed) drive is an electronic controller that adjusts the speed of an electric motor by modulating the power being delivered [1],[2],[3].

Variable speed drives in a pump system are now a grown technology, which can produce large benefits to the user in cost savings and reliability improvements, in the right applications [4],[5].

Pump's drive means a sequence of energy conversions from electrical input power (P_n) $\rightarrow$ mechanical output power (P_m) and then $\rightarrow$ hydraulic power (P_h). Each conversion is described by his specific equations and reference frames [6]. Controlling this electric motor by adjusting speed avoids wasting energy [7]. Appling a VFD to the pump allows control of the pump's speed electrically while using only the energy needed to produce a given flow [8], [9].

When a centrifugal pump is used with an adjustable speed AC drive, the energy costs can reduce by (10 to 60) % of full energy if the pump is designed to operate between (40 to 80) % of full speed [10],[11].

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2. Selection procedure for the basic equipment of the pump drive system

The pump drives system consists of three main units shown in Fig. 1, where the variable frequency drive (VFC) is a device used in A.C drive system to convert AC power to DC, then convert back to AC at a desired frequency, this frequency is applied to control the speed of the induction motor, and the motor will control the pump's speed. The procedure for selection these units as follow:
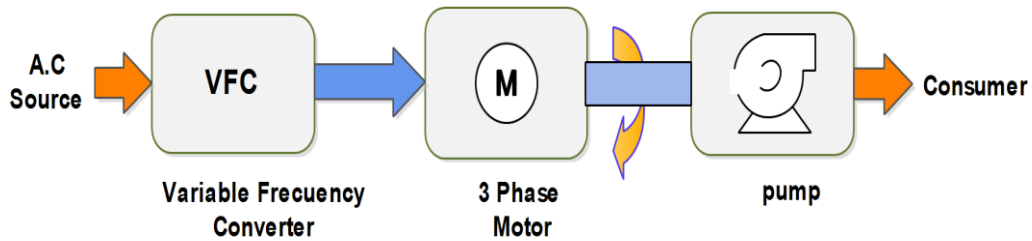
Fig.1 Pump's Drive system diagram

2.1 Selection of the pump

After determining the flow rate, static head and the friction head, the pump can be chosen with the Spaix.NET program given by the VSX- Vogel Software GMBH. The program can be found at the address http://impeller.net.

There are three ways to choose a pump:

- By the coordinates from the *H-Q* plan of the duty point;

- By knowing its name;

- From a catalogue.

In order to search a pump by the coordinates of its duty point, the search starts by specifying the working area of the pump, for example "Water Supply". After that, the nominal pressure head (*H*), nominal flow (*Q*) and the static pressure (*H_g*) are specified, and then select the pump, (Fig. 2).
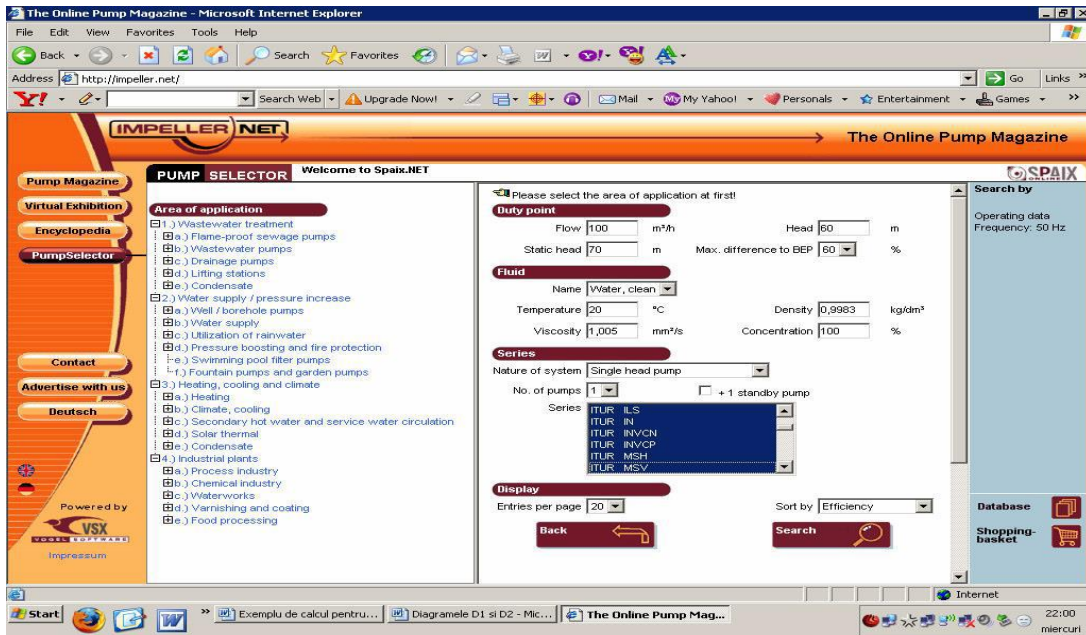
Fig.2. The Spaix.NET program screen

For the *H-Q* characteristic of the pump "**Wilo-Vero Norm –NP 150/315**" and at diameter (356*mm*), the different values for the pump flow rate (Q_p) and the pump head (H_p) will be read. The polynomial's coefficients are obtained by using the MATLAB function for a third degree (equation1), so that 4 coefficients used to calculate the pump's head for any flow rate which are obtained, (table 1).

Table 1

The *H-Q* characteristics of the pump

N	1	2	3	4	5	6	7	8	9	10
Q_p (m3/h)	0	50	100	150	200	250	300	350	400	450
H_p (m)	44	43.8	43.6	43.3	43	42.4	40.5	38.5	36	32

$$H_p = p_1 * Q^3 + p_2 * Q^2 + p_3 * Q + P_4 \tag{1}$$

P1= -0.000000196736597   P2= 0.000042144522145

P3= -0.005811188811189   P4= 43.991608391608416

From characteristics of pump efficiency (E_p), the values of (Q_{ep}) are read at the intersection (E_p) with the curve *H-Q* pump, (table 2). The polynomial's

coefficients are obtained for a fourth degree (equation 2), so that 5 coefficients used to calculate the pump's flow rate for any efficiency are obtained [12].

Table 2

The characteristics of the pump's efficiency

N	1	2	3	4	5	6	7	8	9	10	11	12
E_P %	0	60	70	75	79	80	84	85	84	80	79	75
Q_{ep} (m3/h)	0	150	185	217	250	267	317	360	397	441	456	485

$$\eta_p = P_1*Q^4 + P_2*Q^3 + P_3*Q^2 + P_4*Q + P \tag{2}$$

P_1= -0.000000001098924 P_2= 0.000001586700001 P_3= -0.001394207391363
P_4= 0.582989597568869 P_5= -0.029547605441876

   In order to establish the adjustment area for the speed and for the nominal power of the driving motor it's necessary put the consumer's characteristic line in the same plane with efficiency lines. The working point in the *H-Q* domain is determined by intersecting the consumer's characteristic with the pump's characteristics, (Fig. 3).
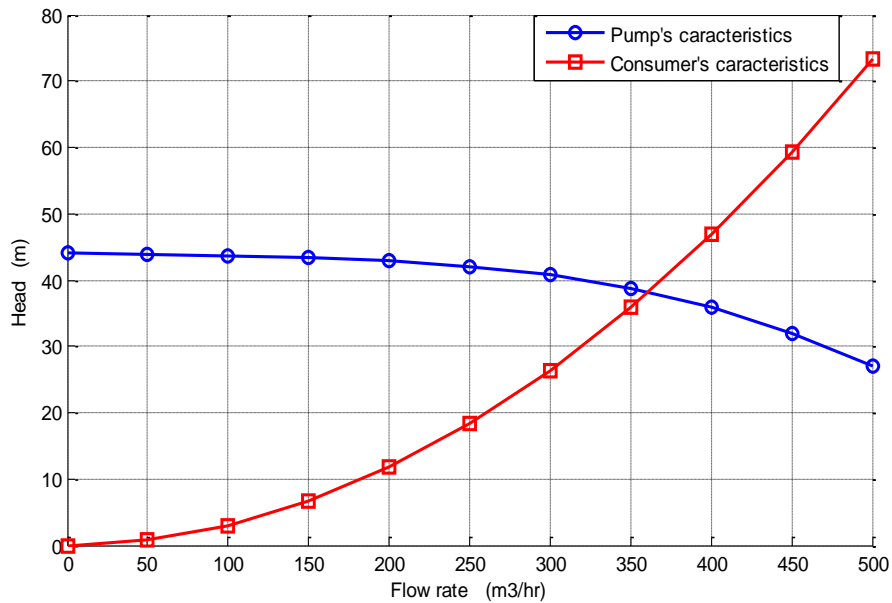

Fig.3. The system's characteristics

A consumer has a characteristic given by the equation 3, and the consumer's constant (K_c) for the minimum hydraulic resistance by the equation 4,where $Hg=0$.

$$Hc = H_g + Kc * Q_n^2 \tag{3}$$

$$K_c = \frac{H_n - H_g}{Q_n^2} \tag{4}$$

The next objective is to obtain an analytic expression for the consumer's efficiency (E_c) and the flow rate (Q_{ec}), the values of (Q_{ec}) are read at the intersection (E_c) with the consumer's characteristic, (table 3).

Table 3

The characteristics of the consumer's efficiency

N	1	2	3	4	5	6	7	8
Ec %	0	60	70	75	79	80	84	85
Qec (m3/h)	0	180	225	270	295	315	335	360

$$\eta_c = P_1 * Q^4 + P_2 * Q^3 + P_3 * Q^2 + P_4 * Q + P_5 \tag{5}$$

P_1= 0.000000004266890 P_2= -0.000002800535874 P_3= 0.000002335161424
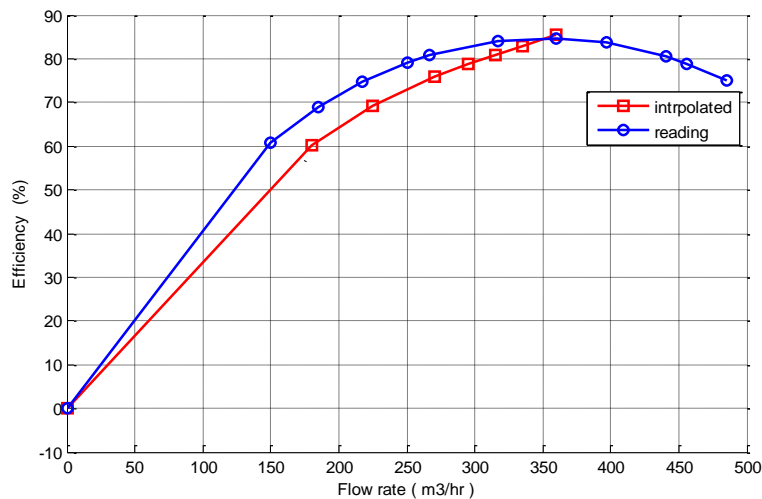P_4= 0.400294670347964 P_5= -0.004389175917163

Fig. 4. The efficiency characteristics

2.2 Selection of the drive engine

The power needed at the shaft (P_m) is obtained from the expression of the hydraulic power at the nominal point $P_h=H*Q$ and from a good estimated duty efficiency [12],[13],[15].

For the illustrated situation in the figures above we have:

$Q =360\ m^3/h,\quad \eta=85\ \%,\quad H_Q=38m,\quad$ 1m colH2O is 10 N/m^2

So that the evaluation of the maximum mechanical power for $Qmax=380\ m^3/h$ leads to:

$$P_m = \frac{P_h}{\eta} \tag{6}$$

$$P_{(max)} = \frac{\rho \times g \times H_{max} \times Q_{max}}{3600 \times \eta_{max}} \tag{7}$$

$$= 49.7\ kW$$

where: ρ is the fluid's density [kg/m^3], g is the gravitational acceleration [m/s^2]

Asynchronous engine will be searched that can easily provide this power (49.7 kW) at the pumps revolution speed (N_p)with the catalogue from the **ABB** Company because they provide with the data needed to determine the parameters from the equivalent schematic chart, (Fig. 5). For this power the low voltage electric motor will use with a cage rotor [12],[13],[14].

| 55 | M2QA 250 M4A | 3GQA 252 301-**A | 1480 | 93.4 | 91.3 | 0.87 | 98 | 7.0 | 354 | 2.4 | 2.7 | 0.78 | 450 | 76 |

Fig. 5 Motor's catalogue

$P_N = 55\ kW$; $V_N = 400V$; $N_N = 1480\ rpm$; $N_1 = 1500\ rpm$; $\eta_{75\%} = 0.913$; $\eta_N = 0.934$; $cos\theta = 0.87$; $I_N = 98A$; $M_N = 354Nm$; $M_m/M_N = 2.7$; $M_p= 2.4$; $I_p = 7$; $J_M = 0.78\ kgm^2$

where: P_N is the nominal power, V_N is the nominal voltage, N_N is the nominal revolution, η_N is the nominal efficiency, $\eta_{75\%}$ is return to 75% of a load, $Cos\theta$ is the nominal factor of the power, I_N is the line's current, M_m is the maximum torque, M_N is the nominal torque, M_p is the ratio between starting torque and the nominal torque, I_p is the ratio between starting current and the nominal current, J_M is the inertial moment of the engine.

2.3 Selection of the frequency converter

We shall choose a converter made by Baldor, a company that offers an online catalogue for converters, (Fig. 6).

Catalog Number	Normal Duty HP	kW	Continuous Normal Duty Amps	Heavy Duty HP	kW	Continuous Heavy Duty Amps	Frame	Height inches [mm]	Width inches [mm]	Depth inches [mm]	Weight lbs. [kg]
						230Vac Input					
VS1PF4100-9	100	75	152	75	55	111	L	24.02 (610)	14.57 (370)	13.29 (338)	92.6 (42.1)

Fig.6. Converter's catalogue

3. Calculating the parameters and powers for the system

From a MATLAB program and for the $Qn = 360 m^3/h$ (in point P), the next parameters for the asynchronous motor are obtained:

$r_2 = 0.015325671$; $r_1 = 0.025688615$; $X_6 = 0.197506956$; $X_{1m} = 2.593732734$; $X_{s2} = 0.107506986$; $X_{s1} = 0.084469775$; $S_m = 0.080264201$; $\lambda = 0.130294145$; $r_{2p} = 0.040337672$; $X_{s2p} = 0.1266834347$.

where: r_1 & r_2 are the stator and rotor resistance, X_{s1} & X_{s2} are the stator and rotor reactance, X_6 is the sum of leakage reactance, X_{1m} is the magnetization reactance, S_m is the critical slip, λ is a constant value (it's very small in comparison with the rest of the terms), r_{2p} & X_{s2p} are the starting parameters. In order to calculate the active power, reactive power, supply frequency and the electric motor parameters in working points P, P1 and P1r (Fig. 7):
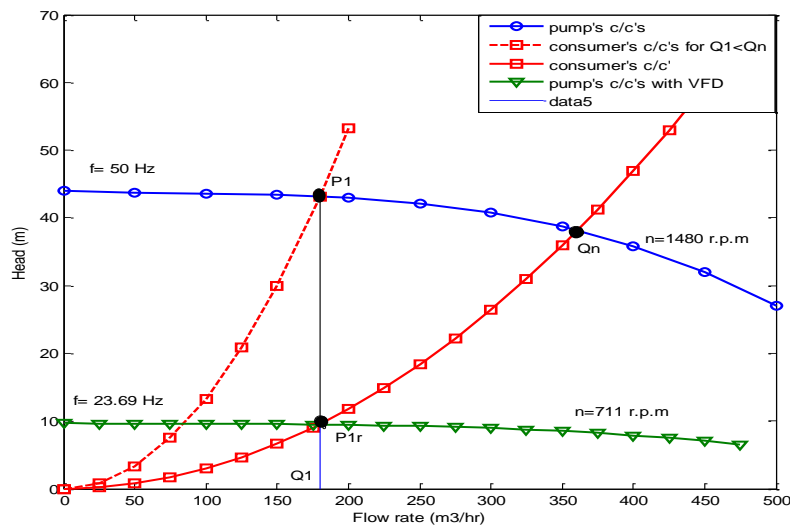

Fig.7. The consumer's characteristic for the flow rates *Q1< Qn*

when the motor is connected directly to the electrical network or connected by using a frequency converter, we assume that the consumer needs **50%** from the nominal flow rate=**180 m³/h**.

3.1 The powers and parameters in the P1

For **Q1=180m^3/h**, the pressure that needed by the consumer and efficiency:

$$H_{p1}= 43.164 \; m, \quad \eta_{p1}=67.84 \; \%$$

From equation 7, the power needed at the shaft P_{mp1} =31815W

The working slip(S) is calculated with the equation 8 and by doing the 2nd degree equation, the slip will result [6]: $S = 0.01$

$$P_{mp1} = M \times \Omega = \frac{2(1-\lambda) \times M_m \times \Omega_1 (1-S)}{(S/S_m) + (S_m/S) + 2\lambda} \tag{8}$$

where: $M_m = 2.7*354 = 955.8 \; NM$, and Ω_1 is the angular synchronous velocity.

By using the equivalent circuit, the voltage absorbed from the industrial electrical network can be calculated:

Z_1=complex(r_1, X_{s1}) Z_b	$Z_1 =$ 0.18161 + 0.59717i
Z_2=complex(r_2/S, Xs2) Z_b	$Z_2 =$ 8.12597 + 0.76003i
Z_m=complex(0, X_{1m}) Z_b	$Z_m =$ 0 +18.33664i
i_1=V_n/[(Z_1+ Z_2)* Z_m/(Z_2+ Z_m)]	$i_1 =$ 44.39821-27.39532i
Cosθ=real(i_1)/abs(i_1)	Cosθ = 0.851

Because the calculations are made in real units the impedances are written as complex and MATLAB can calculate the active and reactive components for the phase voltage [12].

The active power (*Pabs1*) and reactive powers (q_{abs1}) are:

$$P_{abs1} = 3 \times Vn \times real(i_1) \tag{9}$$

$$= 53278 \; W$$

$$q_{abs1} = 3 \times Vn \times imag(i_1) \tag{10}$$

$$= 32874 \; W$$

3.2 The powers and parameters in the point P

For **Q1=180m^3/h**, the pressure that needed by the consumer and efficiency:

$$H_{p1r}= 9.5m, \qquad \eta_{p1r}= 60.27 \%$$

The affinity transformation law for a constant flow rate will provide us with the ratio of the revolution speed in the point **P$_{1r}$** and one from the point **P$_1$**.

$$v = \frac{\Omega_{p1r}}{\Omega_{p1}} = \sqrt{\frac{H_{p1r}}{H_{p1}}} \qquad (11)$$

$$= 0.469$$

The shaft power is calculating from equation 7: $P_{m1r} = 7881\ W$

The relative value for the supply frequency v_1 is calculating by using equations 12 and 13:

$$P_{mp1r} = M \times \Omega_{p1r} = \frac{2(1-\lambda) \times M_m \times \Omega_1(1-S)}{\left((v_1-v)/S_m\right)+\left(S_m/(v_1-v)\right)+2\lambda} \qquad (12)$$

$$\frac{v_1-v}{S_m} + \frac{S_m}{v_1-v} + 2\lambda = \frac{M_m \times \Omega_1}{P_{p1r}}(1+\lambda) \times v \qquad (13)$$

The frequency and revolution speed of the pump will be:

$$f_{p1r} = f_n \times v_1 \qquad (14)$$

$$=23.69Hz$$

$$\Omega_{p1r} = 1500 \times v_1 \qquad (15)$$

$$=711\ r.p.m.$$

By proceeding similar as the precedent point, the parameters will be:

Z_{1r} = complex (r$_1$, v_1 *X$_{s1}$) Z$_b$ Z_{1r}= 0.18161+0.28298

$Z_{2\ r}$= complex (r$_2$/s, v_1 *X$_{s1}$) Z$_b$ Z_{2r}= 10.85846+0.36015i

Z_{mr} = complex (0,v_1 *X$_{1m}$) Z$_b$ Z_{mr}= 0 + 8.68913i

i$_{1r}$= v_1*V$_n$/(Z$_{1r}$+Z$_{r2}$*Z$_{mr}$/(Z$_{r2}$+Z$_{mr}$))   i$_{1r}$=16.5112- 21.39557i

The active and reactive powers:

$$P_{abs1r} = 3 \times v_1 \times V_n \times real(i_{1r})$$ (16)

$$= 9389 \text{ W}$$

$$q_{abs1r} = 3 \times v_1 \times V_n \times imag(i_{1r})$$ (17)

$$= 12167 \text{ W}$$

3.3 The power losses

From equation 6:

$$P_m - P_h = 6705 W$$ (18)

$$P_{mp1} - P_{hp1} = 10233 W$$ (19)

$$P_{mp1r} - P_{hp1r} = 3131 W$$ (20)

3.4 The saving powers

Economic power (P_{eco}) or saving power for Q_1 is given by the two different values of the efficiency for the two working points **P₁** & **P₁ᵣ**, (Fig. 8):

$$P_{eco} = \Delta P_m = P_{mp1} - P_{mp1r}$$ (21)
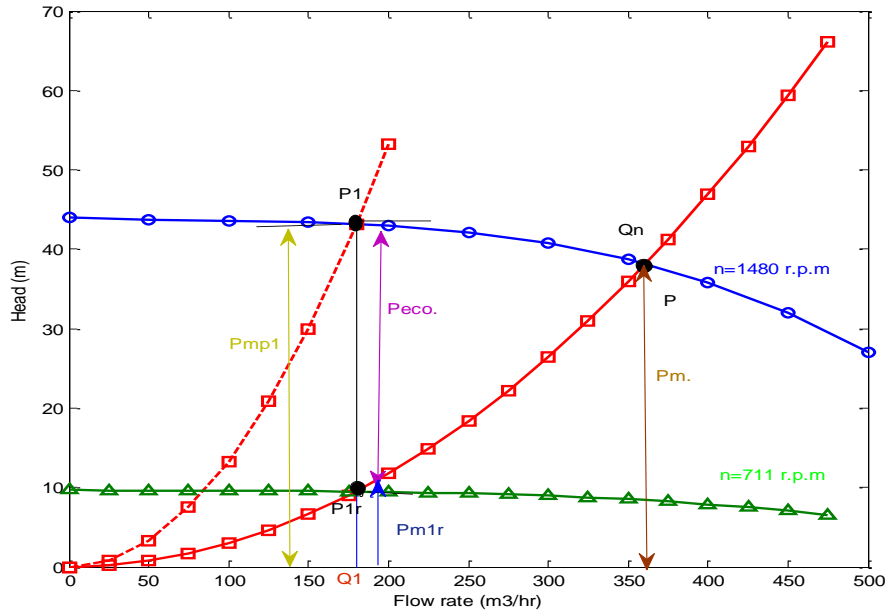
$$= 23934 W$$

Fig.8 The mechanical characteristics of the system

4. Conclusions

- The method that we use it in this paper improved the calculate of saving power of a pump drive and also evaluate electrical performance for this drive by using the parameters from the catalogue and parameter of motor's equivalent circuit. MATLAB programs are used to obtain the all polynomial coefficients of the system. The application of such program gives much better results if they are compared with the use of estimating method.

- The speed control of induction motor using variable frequency drive can save energy according to affinity law. According to this assumption a small reduction in speed can save a large amount of energy.

- All of the saving curves that we get it in our calculation are based upon the difference between horse power input of the pump at constant speed and the input power at reduced speed for each flow at various constant heads.
- The power losses in point P1 with decreased flow rate ($Q_1 < Q_n$) and increased head ($H_1 > H_n$) it's bigger compared with power in point P, because of the increased system friction. And the power losses in point P1r with decreased flow rate ($Q_1 < Q_n$) and decreased head ($H_1 < H_n$) it's smaller

compared with power in point P& P1, because of control the speed of induction motor by using variable frequency drive (Fig. 8).

- Controlling the nominal speed from 1480 rpm to 711 rpm caused by control the nominal frequency from 50Hz to 23Hz (Fig. 7), we get the saving power about 52% of main power by controlling of the flow rate to 50% of the nominal flow rate.

R E F E R E N C E S

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