Allen-Bradley

AC Drives

# Energy Savings With Adjustable Frequency Drives

*Centrifugal Pumps*

Allen-Bradley
Reliance Electric
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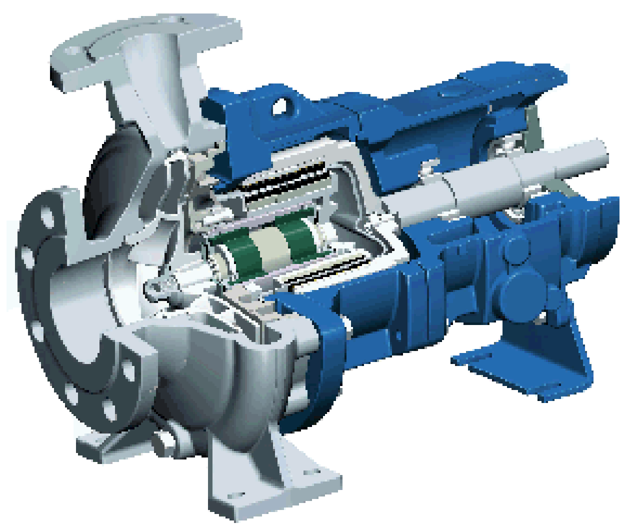
## Pump Categories

- *Positive Displacement Pumps*
- *Dynamic (Centrifugal) Pumps*

## Centrifugal Pumps

Pumps are generally grouped into two broad categories, positive displacement pumps and dynamic (centrifugal) pumps. Positive displacement pumps use a mechanical means to vary the size (or move) of the fluid chamber to cause the fluid to flow. Positive displacement pumps have a constant torque characteristic, where centrifugal pumps are variable torque in nature. Centrifugal pumps impart a momentum in the fluid by rotating impellers immersed in the fluid. The momentum produces an increase in pressure or flow at the pump outlet. This paper will discuss only the centrifugal pump.

A centrifugal pump is a device, which converts driver energy to kinetic energy in a liquid by accelerating it to the outer rim of a revolving device known as an *impeller*. The key idea here is that the energy created is *kinetic energy*. The amount of energy given to the liquid corresponds to the *velocity* at the edge or vane tip of the impeller. The faster the impeller revolves or the bigger the impeller, then the higher the velocity of the liquid at the vane tip and the greater the energy imparted to the liquid.



Creating a resistance to the flow controls the kinetic energy of a liquid coming out of an impeller. The first resistance is created by the pump volute (casing), which catches the liquid and slows it down. When the liquid slows down in the pump casing some of the kinetic energy is converted to pressure energy. It is the resistance to the pump's flow that is read on a pressure gauge attached to the discharge line. A pump does not create pressure it only creates flow. Pressure is a measurement of the resistance to flow.

HEAD – Resistance to Flow

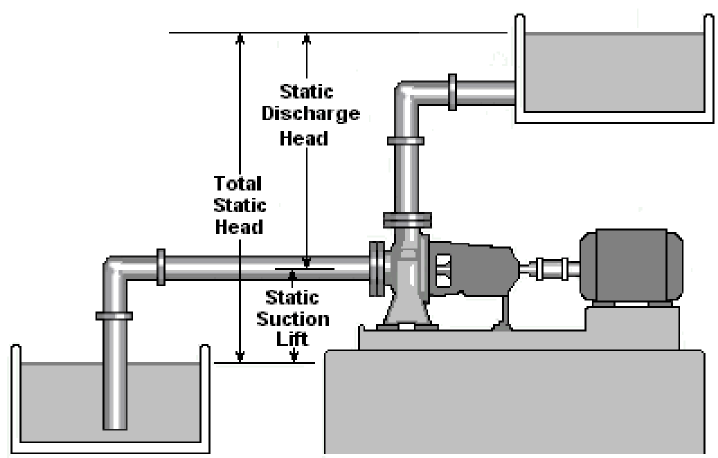
In newtonian (true) fluids (non-viscous liquids like water or gasoline) we use the term head to measure the kinetic energy which a pump creates. Head is a measurement of the height of a liquid column, which the pump could create resulting from the kinetic energy the pump gives to the liquid. The main reason for using head instead of pressure to measure a centrifugal pump's energy is that the pressure from a pump will change if the specific gravity (weight) of the liquid changes, but the head will not change. So we can always describe a pump's performance on any newtonian fluid, whether it's heavy (sulfuric acid) or light (gasoline) by using the term head. Remember that *head* is related to the *velocity* that the liquid gains when going through the pump.

**Example:**
*Imagine a pipe shooting a jet of water straight up into the air, the height the water goes up would be the head.*

All of the forms of energy involved in a liquid flow system can be expressed in terms of feet of liquid. The total of these various heads determines the total system head or the work, which a pump must perform in the system. The various forms of head are defined as follows.

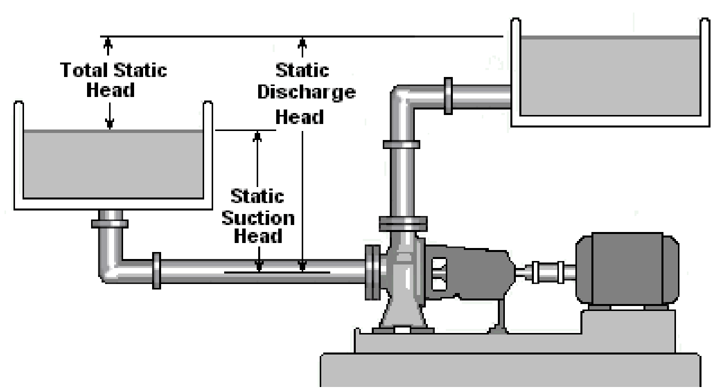
**Pump Terms**

SUCTION LIFT exists when the source of supply is below the centerline of the pump. Thus the STATIC SUCTION LIFT is the vertical distance in feet from the centerline of the pump to the free level of the liquid to be pumped.




SUCTION HEAD exists when the source of supply is above the centerline of the pump. Thus the STATIC SUCTION HEAD is the vertical distance in feet from the centerline of the pump to the free level of the liquid to be pumped.

STATIC DISCHARGE HEAD is the vertical distance in feet between the pump centerline and the point of free discharge or the surface of the liquid in the discharge tank.




TOTAL STATIC HEAD is the vertical distance in feet between the free level of the source of supply and the point of free discharge or the free surface of the discharge liquid.

FRICTION HEAD ($h_f$) is the head required to overcome the resistance to flow in the pipe and fittings. It is dependent upon the size, condition, and type of pipe, number and type of pipe fittings, flow rate, and nature of the liquid. Frictional tables are included in Water Data.

VELOCITY HEAD ($h_v$) is the energy of a liquid as a result of its motion at some velocity *V*. It is the equivalent head in feet through which the water would have to fall to acquire the same velocity, or in other words, the head necessary to accelerate the water. Velocity head can be calculated from the following formula:

$$h_v = \frac{V^2}{2g}$$

Where:
g = 32.2 ft/sec$^2$
V = liquid velocity in ft/sec

The velocity head is usually insignificant and can be ignored in most high head systems. However, it can be a large factor and must be considered in low head systems.

PRESSURE HEAD must be considered when a pumping system either begins or terminates in a tank which is under some pressure other than atmospheric. The pressure in such a tank must first be converted to feet of liquid. A vacuum in the suction tank or a positive pressure in the discharge tank must be added to the system head, whereas a positive pressure in the suction tank or vacuum in the discharge tank would be subtracted. The following is a handy formula for converting inches of mercury vacuum into feet of liquid.

$$Vacuum,\ feet\ of\ liquid = \frac{Vacuum,\ in\ of\ \ hg \times 1.13}{Specific\ Gravity}$$

The above forms of head, namely static, friction, velocity, and pressure, are combined to make up the total system head at any particular flow rate. Following are definitions of these combined or “Dynamic” head terms as they apply to the pump.

TOTAL DYNAMIC SUCTION LIFT ($h_s$) is the static suction lift minus the velocity head at the pump suction flange plus the total friction head in the suction line. The total dynamic suction lift, as determined on pump test, is the reading of a gauge on the suction flange, converted to feet of liquid and corrected to the pump centerline, less the velocity head at the point of gauge attachment.

TOTAL DYNAMIC SUCTION HEAD ($h_s$) is the static suction head plus the velocity head at the pump suction flange minus the total friction head in the suction line. The total dynamic suction head, as determined on pump test, is the reading of the gauge on the suction flange, converted to feet of liquid and corrected to the pump centerline, plus the velocity head at the point of gauge attachment.

TOTAL DYNAMIC DISCHARGE HEAD ($h_d$) is the static discharge head plus the velocity head at the pump discharge flange plus the total friction head in the discharge line. The total dynamic discharge head, as determined on pump test, is the reading of a gauge at the discharge flange, converted to feet of liquid and corrected to the pump centerline, plus the velocity head at the point of gauge attachment.

TOTAL HEAD (H) or TOTAL DYNAMIC HEAD (TDH) is the total dynamic discharge head minus the total dynamic suction head or

$$TDH = h_d + h_s \text{ (with suction lift)}$$
$$TDH = h_d - h_s \text{ (with suction head)}$$

POWER

The work performed by a pump is a function of the total head and the weight of the liquid pumped in a given time period. The pump capacity in GPM and the liquid specific gravity are normally used in the formulas rather than the actual weight of the liquid pumped.

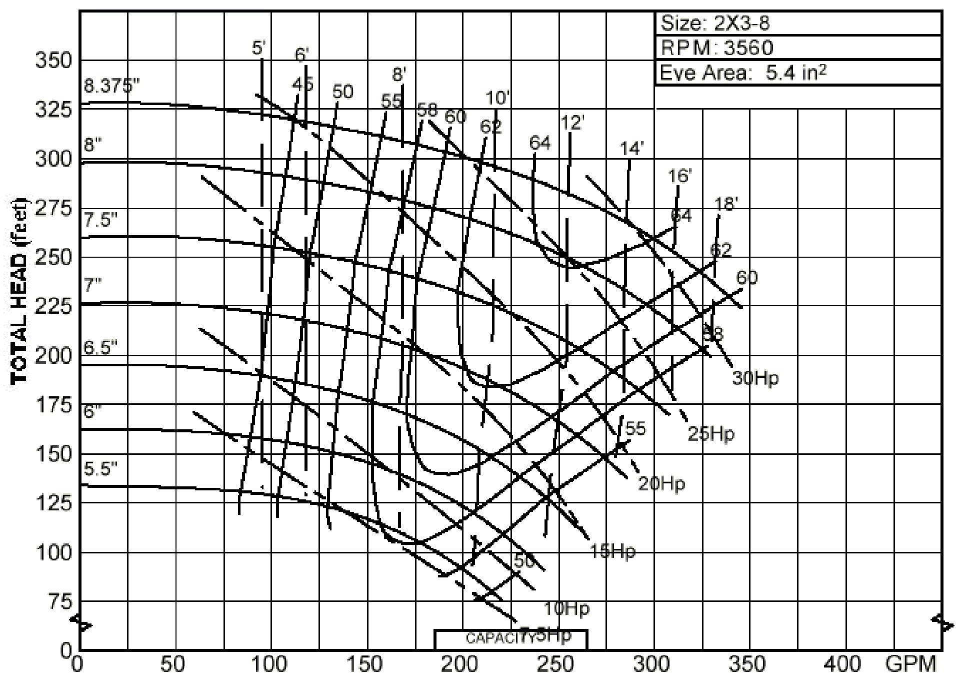
Pump input or brake horsepower (BHP) is the actual horsepower delivered to the pump shaft. Pump output or hydraulic horsepower (WHP) is the liquid horsepower delivered by the pump. These two terms are defined by the following formulas.

$$Water\ HP = \frac{GPM \times Head \times Specific\ Gravity}{3960}$$

$$Brake\ HP = \frac{GPM \times Head \times Specific\ Gravity}{3960 \times Pump\ Efficiency} \quad OR \quad \frac{Water\ HP}{Pump\ Efficiency}$$

## Reading a Pump Performance Curve

The pump characteristics such as flow, pressure, efficiency, and brake horsepower are shown graphically on a pump curve. The first item to look at is the size of the pump.




The size of the pump, 2x3-8 is shown in the upper section of the graph. The numbers 2x3-8 indicate the outlet (discharge port) is 2 inches, the inlet (suction port) is 3 inches, and the impeller has an 8-inch diameter. Some companies may have the number shown as 3x2-8. The larger of the first two numbers is the inlet.

Pump Speed (RPM) is also shown in the upper section of the graph and indicates performance at a speed of 3560 RPM. All of the information is representative of this operational speed.

Capacity or Flow is shown along the bottom of the curve. The various flow levels are all shown for the operating speed of 3560 RPM, but indicate the effect of head as the outlet is throttled.

The left side of the performance curves shows head (ft) generated at the various flow rates.

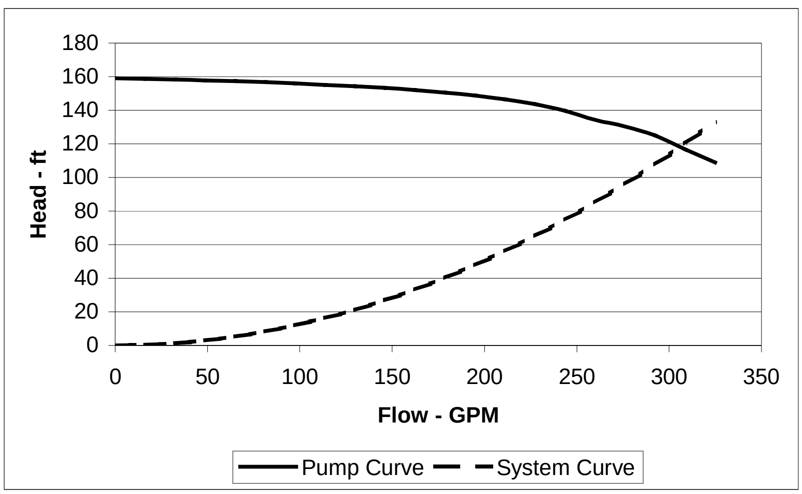
Multiple flow versus head curves are present on the graph, each one represents a different (trimmed) impeller size. For this pump the range of impellers is 5.5 inches to 8.375 inches.

Efficiency curves are overlaid on the graph (vertical lines) and indicate from 64-45% efficiency for this pump. As head is increased flow and efficiency decrease.

Brake horsepower is shown with the dashed lines drawn diagonally from upper left to lower right. BHP curves are shown for 7.5 – 30 horsepower. Using the 8-inch impeller with a flow of 250 GPM, the BHP is approximately 25 horsepower.

## Pump and System Curves

The pump curve is solely a function of the physical characteristics of the pump. The system curve is completely dependent on the size of pipe, the length of pipe, the number and location of elbows, and other factors. Where these two curves intersect is the natural operating point. That is where the pump pressure matches the system losses and everything is balanced.

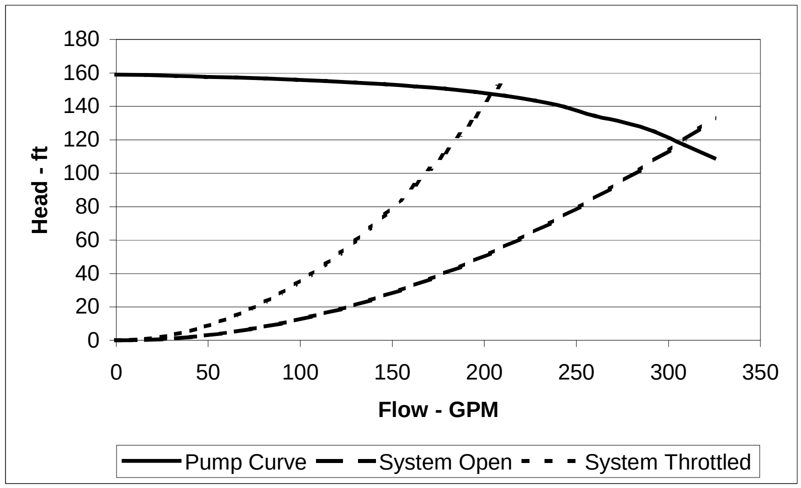



If the system is part of a process that changes often or continuously, then some method of altering the pump characteristics or the system parameters is necessary.

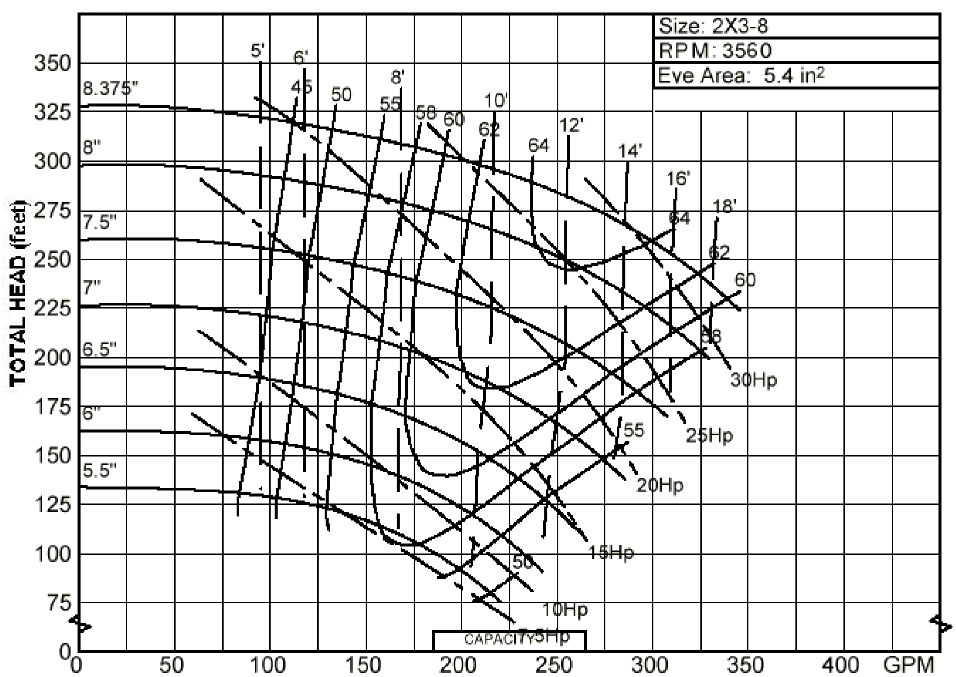
There are two methods used to accomplish the continuously varying flow objective. One method is throttling which changes the system curve by use of a control or throttling valve. The other method is to vary the speed of the pump, which modifies the pump curve.

### Throttling System

With this method, obstructing flow increases the head pressure. A system with two different valve settings is shown below.




For comparison, let's use an example to determine power requirements for the throttling system, then the variable speed system. A pump (with an 8" impeller) operating at a base speed of 3560 RPM is used. This pump is to operate a system requiring a 250-FT head at 250 GPM. See pump curve below.



From the information shown on the graph, we can obtain the various horsepower requirements at the flow rates shown in the table below for a throttling system.

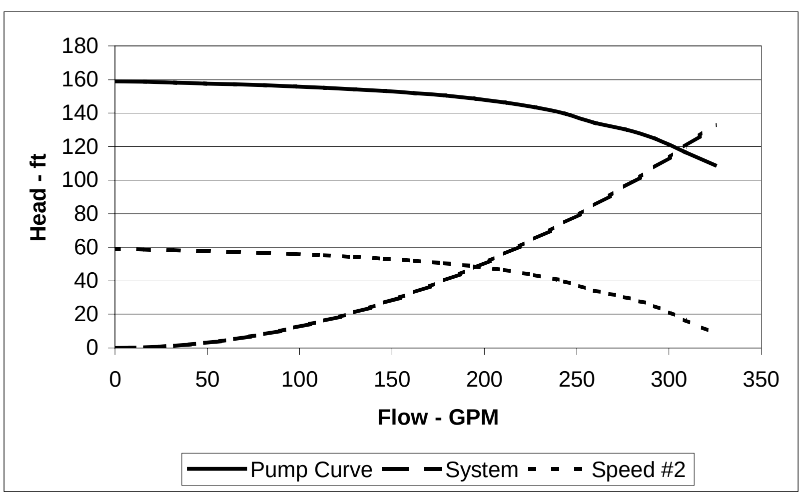
| | | | | |
|---|---|---|---|---|
| GPM | 250 | 200 | 150 | 100 |
| % FLOW | 100 | 80 | 60 | 40 |
| BRAKE HP | 25 | 22.5 | 19 | 18 |

$$Water\ HP = \frac{Flow \times Head \times Specific\ Gravity}{3960}$$
$$= \frac{250 \times 250 \times 1.0}{3960} = 15.78$$

$$Brake\ HP = \frac{Water\ HP}{Pump\ Efficiency}$$
$$= \frac{15.78}{0.64} = 24.67\ BHP$$

## Variable Speed System

In comparison, the variable speed method takes advantage of the change in pump characteristics that occur when the impeller speed is changed.




The lower pump speed changes the pump curve based on the head generated by the velocity of the fluid being pumped. Remember that the head is equal to $V^2/2g$.

## Affinity Laws

A set of formulas that are used to predict the operation of a centrifugal pump at any operating point based on the original pump characteristics is known as the affinity laws.

$$\frac{Q_1}{Q_2} = \frac{N_1}{N_2} \qquad \frac{P_1}{P_2} = \left(\frac{N_1}{N_2}\right)^2 \qquad \frac{HP_1}{HP_2} = \left(\frac{N_1}{N_2}\right)^3$$

Where:
N = Pump speed
Q = Flow (GPM)
P = Pressure (Feet)
HP = Horsepower

Using the same pump example as the throttling system, we can calculate the power requirements for the system when the pump speed is varied.

| GPM | 250 | 200 | 150 | 100 |
|---|---|---|---|---|
| % FLOW | 100 | 80 | 60 | 40 |
| RPM | 3560 | 2848 | 2136 | 1424 |
| BRAKE HP | 25 | 12.8 | 5.4 | 1.6 |

Note: Use 25 HP for $HP_1$, 3560 for $N_1$, 250 for $Q_1$ to fill in the table above.

$$RPM\ at\ 200\ GPM: \quad \frac{Q_1}{Q_2} = \frac{N_1}{N_2}$$

$$\frac{200}{250} = \frac{3560}{N_2} \quad therefore\ N_2 = 2848\ RPM$$

$$BHP\ at\ 200\ GPM = \frac{BHP_1}{BHP_2} = \left(\frac{N_1}{N_2}\right)^3$$

$$\frac{25}{BHP_2} = \left(\frac{3560}{2848}\right)^3$$

$$12.8 = BHP_2$$

Use the affinity laws to calculate the values for the remainder of the operating points.

It is obvious that varying the speed requires much less power. To determine the actual power required, the efficiency of the drive should be factored in. The energy savings will depend on the amount of time the pump is operated at each reduced speed point.

To calculate the actual savings, the brake horsepower must be converted to watts and then multiplied by the hours of operation. The result is then multiplied by the cost per kWh to show the cost to operate the pump at each flow point. Subtract the variable speed value from the throttling value to show the difference in energy cost.

In our example, a flow of 200 GPM when throttled takes 22.5 horsepower. Conversely, with variable speed only 12.8 horsepower is required for the same flow. If the flow is required for 2000 hours a year at 7 cents per kWh, the cost comparison is as follows:

Throttling system:
22.5 HP x 0.746 = 16.785 kW
16.785 x 2000 = 33,570 kWh
33,570 x 0.07 = $2,350

Variable speed system:
12.8 x 0.746 = 9.5488 kW
9.5488 x 2000 = 19,097 kWh
19,097 x 0.07 = $1,337

Savings:
$2,350 –1,337 = $1,013

The example did not have a static head associated with it. A system with static head does change the system curve and the horsepower requirements. The greater the static head a system has the lower the possible energy savings. That is due to the fact that the system curve is flatter so most of the energy is used to overcome the elevation change associated with high static head systems.

[www.rockwellautomation.com](http://www.rockwellautomation.com)

**Corporate Headquarters**
Rockwell Automation, 777 East Wisconsin Avenue, Suite 1400, Milwaukee, WI, 53202-5302 USA, Tel: (1) 414.212.5200, Fax: (1) 414.212.5201

**Headquarters for Allen-Bradley Products, Rockwell Software Products and Global Manufacturing Solutions**
Americas: Rockwell Automation, 1201 South Second Street, Milwaukee, WI 53204-2496 USA, Tel: (1) 414.382.2000, Fax: (1) 414.382.4444
Europe: Rockwell Automation SA/NV, Vorstlaan/Boulevard du Souverain 36-BP 3A/B, 1170 Brussels, Belgium, Tel: (32) 2 663 0600, Fax: (32) 2 663 0640
Asia Pacific: Rockwell Automation, 27/F Citicorp Centre, 18 Whitfield Road, Causeway Bay, Hong Kong, Tel: (852) 2887 4788, Fax: (852) 2508 1846

**Headquarters for Dodge and Reliance Electric Products**
Americas: Rockwell Automation, 6040 Ponders Court, Greenville, SC 29615-4617 USA, Tel: (1) 864.297.4800, Fax: (1) 864.281.2433
Europe: Rockwell Automation, Brühlstraße 22, D-74834 Elztal-Dallau, Germany, Tel: (49) 6261 9410, Fax: (49) 6261 1774
Asia Pacific: Rockwell Automation, 55 Newton Road, #11-01/02 Revenue House, Singapore 307987, Tel: (65) 351 6723, Fax: (65) 355 1733

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