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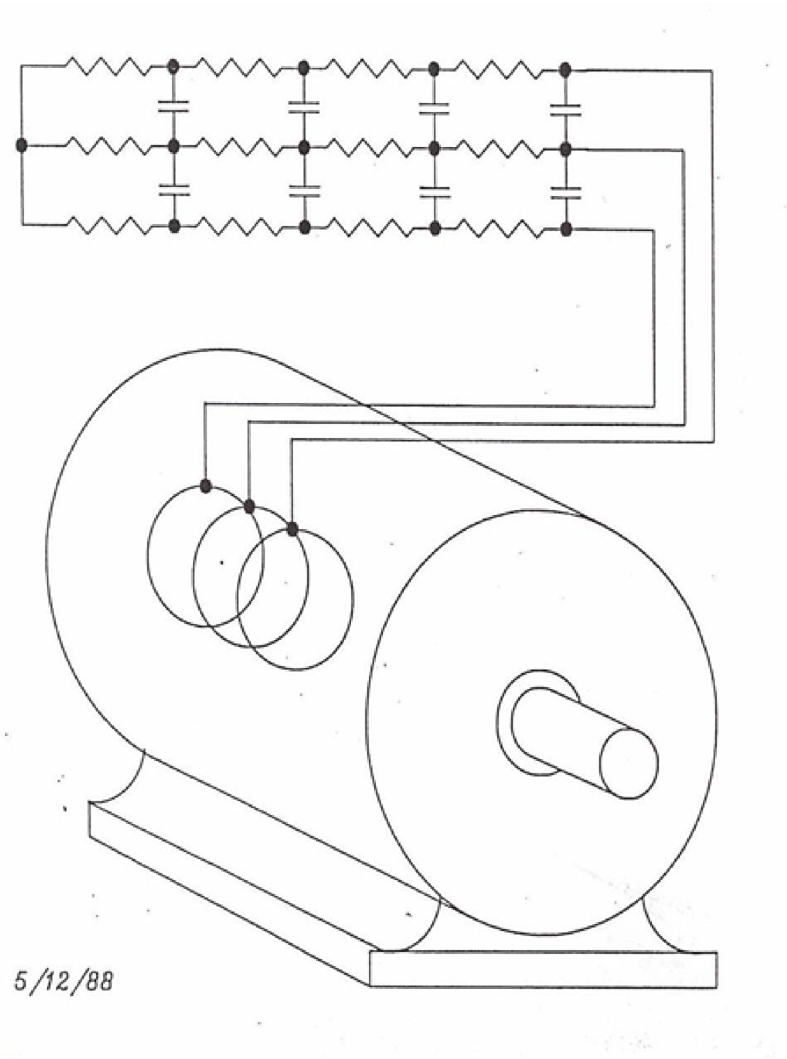
# RESISTOR CONTROL OF WOUND ROTOR MOTORS



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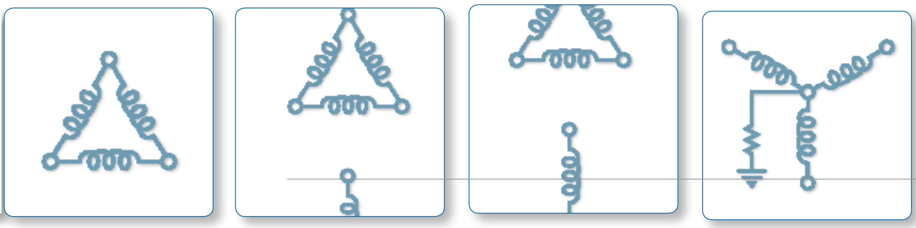

# RESISTOR CONTROL OF WOUND ROTOR MOTORS

The Wound Rotor Induction Motor or Slip Ring Motor is widely used for applications requiring speed control or low starting currents. It is very similar to the Squirrel Cage Induction Motor except that the rotor leads are brought out through slip rings (commutator rings) so that external resistance may be inserted. In fact, if we shorted these three rotor leads together, we would basically have a squirrel cage motor. The beauty of the WRM is that we can control the torque of the motor with external resistors. The purpose of this paper is to show how these resistors are sized and connected for simple speed control or starting duty.

## STATIR CIRCUIT

The Stator, or stationary winding, of the WRM is a three-phase winding which has a cylindrical shape and occupies the outer part of the motor just inside of the motor frame. The three primary leads are usually connected (through a contactor) to the 460 VAC 3ph, 60hz power lines. The three- phase power, applied to the stator windings, produces a rotating magnetic field. The mathematics are complex and will not be covered here. The main thing to remember is that a constantly rotating magnetic field is produced whenever the stator is energized. The speed or RPM of this rotating magnetic field is a function of how many “poles” are created by the windings and the frequency of the incoming power (60 cycles per second in this country, 50 cycles per second in many European countries). With 60hz power, this synchronous RPM is a multiple of 60 such as 360, 900, 1800, etc. The stator part of the WRM is usually referred to as the primary.

Primary volts (usually 460) and primary amps are given by the motor manufacturer and are usually found on the nameplate.

## ROTOR CIRCUIT

The Rotor, or rotating winding, of the WRM is located in the very center of the motor, inside of the stator windings. The rotor shaft spins in bearings located in the ends of the motor frame. One end of the rotor shaft is brought out through the motor housing for coupling to the load. The three rotor leads are terminated with three smooth slip rings. These slip rings form part of the rotor shaft on one end. Three carbon brushes ride against the slip rings.

The secondary rotor leads are terminated at these brushes. A cover plate usually covers these brushes and secondary connection points. Without these slip rings and brushes, the WRM would perform very much like a squirrel-cage motor. The important thing is that now we can insert resistors and control the torque of the motor.

The secondary volts (or rotor volts) and secondary amps (or rotor amps) are given by the motor manufacturer and usually appear on the nameplate.

These two values are necessary to calculate resistor values. If only one of these values and the motor horsepower are available we can calculate the other value with reasonable accuracy. See equation 2 & 3. The secondary volts can be measured by locking the rotor so that it cannot turn, lifting the brushes and measuring between any two rings. The stator must be energized when making this measurement. EXTREME CARE SHOULD BE EXERCISED WHEN MAKING THIS MEASUREMENT. If existing resistors are already connected to the motor, disconnect all three ring leads and then measure between any two leads. Now that we have a basic understanding of the stator and rotor (and their ratings), we can begin to see how they interact to give us desirable motor action.

## THE COMPLETE WOUND ROTOR MOTOR

The wound rotor motor is something like a rotating transformer with a stationary primary winding and a rotating secondary winding. It gets a little more complicated as the speed of this rotating transformer affects its parameters. If we can begin to understand how the motor parameters change with speed, we can calculate what the voltages and currents are doing at any instant of time. If we know what the rotor voltages and currents are, we can calculate the necessary resistance values. Two very important relationships must be understood to fully grasp the resistance calculations. One is the relationship between speed and rotor volts and the other is the relationship between rotor current and motor torque.

The secondary rotor voltage is at its maximum (nameplate) value when the stator is energized, the rotor is at rest and no rotor current is flowing (open circuit). This voltage decays linearly with an increase in speed. If the rotor could turn the same speed as the stator's magnetic field, the rotor voltage would be zero. Actually, the rotor can never turn as fast as the synchronous speed because a small voltage is always necessary to maintain motor torque. At 50% speed, the secondary volts are 50% of its nameplate value. At 25% speed, the rotor voltage is 75%.

The difference between the synchronous speed and the rotor speed is called the slip. The slip is expressed as a percentage. For example, the slip at standstill is 100%. The slip at 90% (of synchronous speed) is 10%. As we said above, the slip can (never reach zero. Normally, a WRM will have about 3 to 10 percent "internal motor slip" with no resistance in the circuit. In other words, the full-load speed of the motor is about 90 to 97 percent of the synchronous RPM. This internal slip generally decreases as the size of the motor increases. The efficiency generally improves with size of motor. A 300 H.P. motor may be 96% efficient with 3% internal slip while a 3 H.P. motor may be only 83% efficient with 10% internal slip. Slip may also be thought of as "percent speed reduction". 30% slip is the same as 30% speed reduction. The slip at any speed is simply 100% minus the %speed. At 60% speed, the slip is 100% - 60% = 40%.

The other very important relationship to remember about wound rotor motors is that rotor current and rotor torque go hand in hand. If you double the rotor current, you double the rotor torque. If you want 50% starting torque, then you size the resistors to allow 50% rotor current. If we know the horsepower of the load at a certain speed, we could calculate the torque and thus the rotor current under those conditions

An interesting characteristic of the WRM is the frequency of the rotor current. It is 60 cycles per second at standstill and decays linearly to zero at synchronous speed. At 50% speed, the frequency is 30 cycles per second. Because of this, current measurements with analog and many digital meters are inaccurate. A true RMS meter is required to measure currents at these lower frequencies.

Once again, the two relationships to remember about WRMs is that rotor voltage is maximum at standstill and decays linearly with an increase in speed and that there is a one to one relationship between rotor current and rotor torque.

## OHM'S LAW AND THE WOUND ROTOR MOTOR

The basic relationship, in the electrical field, is Ohm's Law. Stated simply, it says that the current (in amps) is equal to the voltage (in volts) divided by the resistance (in ohms). If we want 50 amps of current to flow through a resistor when we apply 150 volts across it, then its resistance must be 150 volts divided by 50 amps = 3 ohms. This simple type of calculation is the basis for sizing motor control resistors.

Resistors are required in each leg, or phase, of the rotor circuit. These three identical resistors are, almost without exception, WYE connected. In other words, the three phases are tied to a common neutral point. The secondary voltage (from nameplate or measured) is a line-to-line value. The voltage across WYE connected resistors is a line-to-neutral value. To get from the line-to-line value to the desired value, simply divide by 1.732 (square root of three). For example, if the secondary volts are 200, the volts across the resistors will be 200 divided by 1.732 = 115.47 volts.

*Also used with potential transformers for higher voltage systems.

Now, if we know the desired rotor current (or torque, as they are related), we can calculate the resistance of these three WYE-connected resistors. See figure 2, for a typical WRM resistor circuit.

Let’s work through a simple example to tie all this together. A 5 H.P. WRM has a secondary voltage of 140 and secondary amperage of 19. We want to size a starting resistor to limit the starting torque to 50% of its full load (nameplate) value. What is the resistance of the three WYE connected resistors? Well, the voltage across these resistors will be 140 divided by 1.732 or 80.83 volts. The current required to produce 50% torque is simply 50% rated current or 0.50 times 19 amps or 9.5 amps. To obtain the ohms of the resistors we divide 80.83 volts by 9.5 amps to get the required 8.51 ohms per phase. If we connect one side of each resistor to the slip rings and we tie the other sides of the resistors together to form a common point, then when we energize the stator, we will develop the required 50% starting torque. In fact, we can now develop a general formula to calculate the required resistance per phase for WYE connected resistors in terms of motor parameters;

SECONDARY VOLTS x PERCENT SLIP RESISTANCE/PHASE = ----------------------------------------
SECONDARY AMPS x 1.732 x PERCENT TORQUE

We can use this formula to calculate starting resistors (as we did above) by making the slip = to 100% or 1.0 We can also use this formula to calculate resistors for speed reduction applications if we know what the torque should be at that point. For example, if we wanted resistors to slow the motor down 25% at rated torque, then we would use a % slip value in the formula of 25% (same as % speed reduction) and a % torque value of 100%.

Some other very useful formulas for WRM calculations are shown below;

EQ 1: Horsepower = Sec volts x Sec amps x .0021 (90% efficiency) EQ 2: Sec Volts= Horsepower / Sec amps x .0021
EQ 3: Sec Amps = Horsepower / Sec volts x .0021

These are helpful when complete information is not available or as a check. It is always a good idea to see if the horsepower given agrees with the rotor data given. Older motors tend to be less efficient and have high current/low voltage rotors. Newer motors tend to have high voltage/low current rotors.

The secondary volts are almost always higher than the primary volts.

## MULTIPLE STEP / SPEED CONTROLS

The resistors we have discussed so far have been a single step of resistance in each phase to limit starting torque or for a single speed point. Most controllers require several steps of resistance to smoothly accelerate the load or to provide the various speed points required by the application. Controllers with five speed points are most common. These controllers generally start the motor with all resistance in the rotor circuit and then progressively short out portions of the resistor until finally, all resistance is shorted out and the motor is up to full speed. Refer to figure 2 to see how these multi step resistors are connected. The contactors Al, A2, A3 and A4 are used to short out portions of the total resistance. What these contactors effectively do is move the neutral connection closer and closer to the “no resistance” or ring short condition.

For a five-speed control, there are four steps of resistance. The fifth speed is with all resistance cut out. Therefore, there is always one more speed point than steps of resistance. There is one exception to this rule. Some arrangements use permanent, resistance. A permanent resistor, like the name implies, refers to resistors that stay in the circuit continuously.

Permanent slip resistors are sometimes used with special motor designs to reduce internal heating of the motor. They are often associated with WRMs using solid-state variable frequency controllers. The important thing to remember about permanent slip resistors is that they must be rated for 100% of the secondary amps and that the number of speed points is equal to the number of steps of resistance.

We know how to calculate single-step resistors based on the general formula. There are a few different ways to determine the resistance values for each step of a multi-step controller. Control manufacturers generate tables to use with their controls. These tables list multipliers to use times the ratio of rotor volts divided by rotor amps. In these tables, rotor volts are often referred to as Es and rotor amps as Is. A table may show that the first step from Rl to R2 should have a value of .77 X Es/Is. Therefore, these tables work for all different horsepower motors. The tables also have data on the current ratings required for different steps.

Well that's all fine and well if you have these tables, but chances are you won't. How then, should we proportion out the various steps for smooth control? One way is to use the general formula, plugging in the desired slips and torques desired at the different speed points. The important thing to realize here is that the general formula gives the required value of resistance LEFT IN THE ROTOR CIRCUIT. To obtain the value of resistance in a specific step, you must subtract the required (calculated) resistance from the total resistance. For example, suppose we calculate the total ohms required for 50% starting torque to be 10 ohms. Then, on our next controller point, we calculate that we need 4 ohms to give the desired Performance. The resistance value of the first step of resistance then would be 10 - 4 = 6 ohms. It is very important to know the difference between per step values and left in circuit values. The formula gives you the left in circuit values. We must subtract these values from each other to get the per step Values. The motor is concerned with the resistance left in, but the resistor designer must work with the per step values. This is especially critical because these steps very often have different current ratings.

I will now work through a simple example to show this method of calculating the various steps of a five speed controller. We will work with A 75 Horsepower, 385 rotor volt, 90 rotor amp motor. The following speeds and torques are required:

| STEP | % SPEED | % SLIP | % TORQUE | | OHMS REQ. | OHMS/STEP |
|---|---|---|---|---|---|---|
| 1st | 0 | 100 | 25 | 9.88 | 6.35 | |
| 2nd | 0 | 100 | 70 | 3.53 | -1.55 | |
| 3rd | 0 | 100 | 125 | 1.98 | .99 | |
| 4th | 60 | 40 | 100 | .99 | .99 | |
| 5th | FULL | MOTOR | RATED | ALL CUT OUT | | |

By using the above data and plugging it into the general formula, we can generate the values listed above under ohms required. The per step values are obtained by subtracting the required ohm values from each other. For example, the first step (Rl to R2) is obtained by subtracting the 3.53 value from 9.88 The next step (R2 to R3) is obtained by subtracting 1.98 from 3.53 The third step (R3 to R4) is obtained by subtracting .99 from 1.98 The last step is simply .99 ohms or .99 minus zero. Notice that if you add all of the per step values together, you get the 9.88 ohms. This value is called the total per phase.

Another method of determining step values of resistance for a multi speed control is by first calculating the total per phase value that gives the desired starting torque and then progressively cut the resistance in half with each new speed point. If we had done this with the above motor, we would start with the 9.88 ohms, and then cut out half or 4.94 ohms. On the next point, we would cut the resistance in half again or cut out 2.47 ohms. Next, we would cut out 1.235 ohms and for the last speed; we would simply cut out any remaining resistance which (in this case) would be 1.235 ohms. The per step values are thus;

| STEP | OHMS/STEP |
|---|---|
| lst | 4.94 |
| 2nd | 2.47 |
| 3rd | 1.235 |
| 4th | 1.235 |

TOTAL PER PHASE: 9.88

Yet another way that these values may be specified is a percentage of the total ohms. The above example has 50% of the total in the first step, 25% in the second, and 12.5% in the last two steps.

With all methods, a trend appears. There is a geometric progression of the per step values. Most of the resistance is in the first step and smaller and smaller portions are cut out as the motor is accelerated. You would never see a control with the resistance evenly divided.

In the absence of control manufacturer's resistance tapers or speed-torque data, the following tables may be used to split the total ohms per phase into per step values for smooth starting and acceleration:

| Number of resistance steps | Percentages of steps | |
|---|---|---|
| 2 | 70%, 30% | |
| 3 | 60%, | 30%, 10% |
| 4 | 50%, | 25%, 15%, 10% |
| 5 | 50%, | 25%, 12%, 8%, 5% |

Now we have a pretty good idea of how the resistance values are calculated for starting, accelerating and speed regulating with multi speed point controls. We can use control manufacturers data tables, the general formula in terms of slips and torques, the "cut the resistance in half" method or the table above if we know the total ohms per phase. Once we know the resistance values, we must now determine the current ratings required.

## RESISTOR CURRENT RATINGS

Power resistors are given a current rating which will heat their element 375 degrees Centigrade above the ambient temperature. If we square this current value and multiply it by the resistor's ohmic value, we get the resistor's wattage rating. For example, a 2 ohm, 50 amp rated resistor has a wattage rating of 50 x 50 x 2 = 5,000 watts or 5 kilowatts (5KW). Wattage ratings are sometimes given for smaller-power resistors. To calculate the current rating, divide the wattage by the ohmic value and then take the square root to get the current value. For example, a 10 ohm, 400 watt resistor has a current rating of the square root of 400 divided by 10,or the square root of 40 or 6.32 amps. These current-ratings are needed for motor control applications.

Let's start with the easiest resistors to determine current ratings for. This would be continuous rated resistors such as speed control resistors and other high duty applications requiring continuous ratings. These type resistors generally require a current rating that is equal to or greater than the motor's rated rotor current (secondary amps). In other words, a 385V/90A motor would need resistors rated at least 90 amps continuous. All steps may not require this full 90 amp value though. There are times when we can reduce this value on the first step or two. If the first step will only allow 50% current, the continuous rated resistor for that speed need only be rated for 50%. Class 92 crane resistors are a good example.

Continuous rated speed-regulating resistors are often associated with pump drives. These centrifugal loads are not linear like machine loads and require more resistance for a given speed point. The torque required at a specific speed is found by squaring the percent speed to get the percent torque. For example, at 60% speed, the torque is .60 x .60 = 36% torque. This means we can reduce the current ratings of the resistors on the slower speeds. At 50% speed, we can use resistors rated for only 25% of the rotor amps. At 80% speed, the rotor current is 64% of its maximum value and at 90% speed, it is 81%. Speed regulating resistors are not sized below 50 percent speed due to very poor speed regulation below this value. Sometimes, these resistors are given a service factor. A service factor is a multiplier used to overrate the resistor's current ratings by some value. A 1.15 service factor is common in pump control resistors and simply means multiply all the resistor

The current ratings for continuous rated resistors are the easiest to determine because they, very often, are the same as the rated amps of the rotor. Centrifugal pump and fan loads draw less current at lower speeds (and allow lower current rated resistors on these steps) but usually require about a 1.15 service factor. The more difficult category of resistors to determine/current ratings for are the one's involving duty cycles. The duty cycle describes the on an off times during which the element is heated and allowed to cool. This may occur just once as in the case of infrequently used starting resistors or grounding resistors or may occur repeatedly.

NEMA has established duty cycle classes that are commonly used for motor control purposes. These are listed below with a description of the on and off times and the appropriate multipliers used to establish resistor current ratings.

If the duty cycle is more complicated, testing may be required to determine the appropriate current rating. If the on time is at least 10% of the total cycle time the following formula may be used;

on time
square root of ---------------- times 1.15
total cycle time

This number is the multiplier to use times rotor current to get the resistor's current rating. For example, if the 90 amp motor sees a duty cycle of 15 seconds on out of each 60 seconds, then the resistor current rating multiplier should be the square root of 15/60, (or .50) times 1.15 = .575 If we now multiply this .575 times the 90 amps, it tells us that we need a resistor rated 52 amps continuous. Because the duty cycle allows the resistor to cool 75% of the time, we need a resistor that is about 1/3 the size of a continuous rated resistor. As you can see, the duty cycle and proper sizing of resistors will greatly affect the size (and cost) of motor control resistors. This is especially important in high horsepower applications where space is limited.

On multi step controls, use the above method for determining the current rating for the last step. The previous steps may have even lower current ratings because they see shorter on times. It makes sense that the resistors that are cut out first would not have to be rated as heavy as the last step.

There is no solid answer, short of testing, about how much to lower these ratings. The on times become too small to make the above formula useful. One method I have used is to determine the rating for the last step and then lower each previous step to the next lower current rated resistor available.

For the one-shot duty cycle resistor (where the off time is sufficient to allow the element to cool all the way back down to ambient temperature) the required rating is a function of the particular element's heating curve. The slope of this heating curve is primarily a function of the element's mass and the amount of current applied. If an element of insufficient mass is used, it will overheat. For stainless steel power resistors, the following formula will determine the required mass.

If heat curves or other element data are not available from the resistor manufacturer, the following conservative rules should be followed; Do not overload a 5 second on-time rated resistor more than six times its current value. Do not overload a 10 second on time rated resistor more than three times its current value. This should prevent exceeding the 375 degree C rise allowed on the surface of the element. (Assumes cold element)

# CRANE CONTROL RESISTORS

One of the most common applications of wound rotor motors is overhead cranes such as those used in steel mills and shipyards. Here the resistors are generally used with five-point, reversing magnetic controllers for a combination accelerating, speed regulating and stopping control of the load. To reverse the direction of any WRM, simply swap any two of the three stator (or rotor if you wish) leads. If this is done while the motor is going full speed in one direction, the motor will abruptly retard the load with a countertorque.
This jerky braking action is usually applied in 3 or 4 short “plugs” and is often called plugging. During this initial plugging, the rotor voltage across the resistors can approach twice the normal rotor voltage! The resulting high plugging currents through the resistors can easily overheat the first step of acceleration. Controls for traversing drives such as bridges and trolleys use reversing and plugging controls. The resistors used with these controls need more current capacity in this first step than would normal “non plugged” resistors. Normal crane duty resistors need a first step current rating of at least 30% of the rotor amps. Higher duty classes may need a 40 or even 50% rating.
Most crane-resistors using magnetic contactor controls fall into a NEMA class 162 duty cycle rating and have a starting torque of 50%. Second point torque is around 125% with 150% peaks on remaining points possible. The 50% torque step is used for precise location of the hook or to remove cable slack. Second point usually will accelerate the-load.
Bridge cranes bring up an interesting characteristic of wound rotor motors. The bridge may have a long distance to travel and long accelerating times in lower speeds. Even in these lower speeds (with lots of resistance in the circuit) the motor will 7C) try and reach its synchronous speed. This is because of the reduced load after accelerating the load up to speed.

Sometimes crane resistors are sized for only 25% starting torque. This is more common on bridges and hoist with eddy current brakes. In the case of the bridge, it may be to reduce plugging current, softer starting or extended slow speed operation (as may be required when converting over from cab to pendant controls). Hoists using countertorque lowering controls use specially rated resistors. Sizing of these resistors is best left to the control or crane manufacturer. Usually, the current ratings are higher and more resistors are furnished than normal types of controls.
Some older cranes use sleeve bearings instead of roller bearings and therefore required more “break free” torque for starting. These cranes will very often require NEMA class 163 resistors that allow 70% starting torque instead of the normal 50%.
Below is a 5 speed resistance taper suitable for use with bridges and trolleys with reversing plugging controls. This same taper is also suitable for reversing hoists with mechanical load brakes or eddy current brake controls. Notice that NEMA class 162 is standard duty, 172 heavy duty and 92 continuous duty. The same resistance values are used, but the current ratings go up. More resistors are required for the heavier rated classes.
Class 152 resistors are sometimes specified but I do not recommend them. There is very little cost savings and the marginal designs will allow no abuse. In fact, the heavier class 172 resistors are a real bargain if you are having any resistor problems at all. They will have more current capacity on every step and will therefore run cooler than before. This translates into longer life. Of course, the class 172

# STARTING DUTY RESISTORS FOR MACHINE LOADS

Wound Rotor Motors are often associated with high inertia loads such as steel mill drives, crushers, large presses, etc. because of their high starting torque and low starting current. Resistors are often used to start these machines with a five point magnetic controller. NEMA class 135 is very common for starting machines of this type. On high duty applications, NEMA class 155 or even 165 may be required. These classes call for a starting (or inrush) current of 150% of the rotor amps.

A squirrel cage motor, on the other hand, will draw about six times its rated current when started across the line and about three times with reduced voltage starting. With very high inertia loads and very long accelerating times, large horsepower drives very often rely on the Slip Ring motor with its controllable starting torque feature. The higher duty classes use the same ohmic values but increase the current ratings. The following resistance tapers can be used for starting duty resistors. They are valid for fan and pump loads that often use the lighter classes 115 and 135.

## UNBALANCED SECONDARIES - DRUM CONTROLS

Most controls for wound rotor motors use balanced (or symmetrical) secondary resistors which means that the same ohmic value is used in each phase. Some older controls may have steps that are not balanced. If we take a balanced set of secondary resistors that would normally allow 100% starting torque and open up one phase (break its connection to the neutral point of the wye connected resistors), then we would get 50% torque. I know of one crane builder who takes advantage of this. They use class 164 resistors with only three steps of resistance. Class 164 resistors allow 100% starting torque.

They start with the open secondary to get the normally required 50% starting torque and then switch to balanced phases for the 100% torque. This eliminates the first step of resistance but is not necessarily good for the motor. The Manual Drum Control is a heavy-duty rotary switch used to manually switch resistors in and out of the secondary circuit. The way these drum controls usually work is to have an off point (completely open secondary) for the first point, the open secondary like above, then all three phases in. The resistance in each phase is cut out one phase at a time. There are sometimes balanced points on these controls but for the most part they are unbalanced. Usually the resistance values are staggered so that the imbalance is never too great. The nice thing about the drum control is that is usually has 11 or 13 speed points. They are often used for accurate speed regulating duty on machines such as wire drawers or other older equipment where slight changes in speed may be necessary. The disadvantage is that they are subject to operator abuse for starting duty. The operator may switch the resistors out too quickly. These controls may be recognized by their unusual terminal markings (Rl to R3, R3 to R6, etc instead of Rl to R2, R2 to R3, etc.).

The resistors for these manual drum controls are a little tricky to size. For class 162 crane resistors and an eleven point control, use class 164 resistors with only three steps in each phase. We can use the same balanced resistors we used with a magnetic control, but keep in mind that they will be unbalanced on most points. Terminal markings, manufacturer, and any data on the old resistors are helpful when reworking an old drum setup.

## SOLID STATE CONTROL OR THE WRM

Modern technology has given us the ability to vary the frequency of the power fed to the stator of the WRM. This allows infinitely adjustable speed control.

This is very desirable for crane and other controls requiring precision positioning. Secondary resistors are, however, still used for starting and permanent slip resistance. Some very elaborate-installations have a completely separate magnetic/resistor control to “back up” the solid-state control should it fail. The solid-state controls offer many advantages, including power savings, and are approaching magnetic controls in reliability and cost.

Another solid state control used with wound rotor motors is the slip recovery system whereby the power from the rotor circuit is regenerated back into the incoming stator power circuit in an elaborate feedback scheme rather than being wasted to resistor heat. This type control is especially desirable for water, sewer and slurry pumps which use speed regulated wound rotor motors. On the slower speeds, the power consumption is reduced significantly.

Although many solid-state controls will work well with a simple squirrel cage motor, wound rotors are often used because of their low starting current - high starting torque characteristic. The solid-state devices are better for speed regulating than starting e motor. Also, the WRM has an option of resistor control, should the solid state control fail.

## TYPES OF POWER RESISTORS

Most power resistors used for motor control have an open element made of stainless steel. This special stainless steel is temperature compensated so its resistance will only increase about 6% at rated current (375 degrees C rise above ambient). Normal stainless steel would increase in resistance about

30% at this temperature rise. The element is usually in form of grids stamped from sheet steel or in the form of a ribbon wound on its edge into a helical coil.

In the grid type, the individual stamped grids are stacked onto mica insulated tie bolts to form a grid bank. The banks usually have the two end terminals plus several intermediate taps. This bank may contain from about twenty or so grids to over one hundred and fifty. A standard "mill bank" size grid resistor has developed over the years that is 26-1/2" long, 12" deep and 6" high. These mill banks have an end frame or channel on each end for mounting and stacking the units together. The flanges on these end frames are about 1-1/2" wide and have two holes in each flange that are 6" apart and for 1/2" bolts. These units are often stacked into mounting racks with screened covers. It is convenient to interconnect these banks with solid copper bus bars bolted to the terminals. The wattage rating of a mill bank is typically around 5 or 6KW. Insulated sections are available to isolate all three phase within one grid bank. Also, different current rated grids may be mixed to give the required current taper. This avoids overrating of intermediate steps and keeps the size down. The grid type offers a very high surface area for rapid cooling and is the best choice for high shock and vibration applications requiring a continuous rating of 20 to 200 amps.

The second type resistor mentioned above uses an element formed by winding a strip of stainless steel on its edge (the hard way) into a coil. This coil wound onto and supported on ceramic insulators that have teeth on them to separate the turns of the coil. The insulators are in turn supported by a flat bar that serves as the main mounting member with slotted mounting holes on each end. The length of the coil is determined by the number of ceramic insulators used. A size five, for example, is five insulators long.

The outside diameter of the typical edgewound resistor is about 2" with some units as large as 5". A size five edgewound of the 2" O.D. variety is rated about one KW and is about 16" long. These smaller units are mounted in "banks" similar to the grid banks. These are economical resistors for low shock and vibration applications that require a continuous current rating of 10 to 100 amps.

For power resistors rated below about 25 amps wire wound resistors are often used. These typically consist of a NiChrome or Nickel-Copper alloy wire wound onto a ceramic tube or form. The end terminals consists of bands welded or bolted onto the end of the ceramic. The wire element may be exposed or coated with a high temperature cement or enamel. Adjustable and fixed taps are often available. These units are usually mounted with some type of "L" brackets. These are the most economical choice below 20 amps.

At the other extreme, resistors rated above 200 amps are usually made of one continuous ribbon of stainless steel that is formed into a serpentine fashion and support between end frames for mounting like grid type mill banks. Large stainless steel end terminals and taps usually have two holes for bolting lugs or bus bar. The ribbon may be embossed with stiffening ribs to prevent warpage under overloads. These resistors have very high surface areas and higher wattage ratings than grid banks (usually 8 to 10 KW per bank). This is definitely the best choice for high- current rotors and continuous duty, high horsepower applications. The continuous strip resistor banks, like the grid type are very sturdy and will take severe shock and vibration better than any other type. These resistors will mount in the same racks with the grid type and are often mixed. No isolated sections are available in the strip type resistors.

Most resistors are rated for a 600 volt insulation class. For higher voltage applications, consult the resistor manufacturer. They may offer special end insulation or secondary insulation.

Poor terminal connections are a common source of premature resistor failure. They are usually due to loose terminal hardware. Heat at the terminals can be reduced by-using bronze bolts instead of steel bolts. This is due to the very high copper content. Also, Belleville type spring washers will keep the hardware tight. The terminal plate and lug should be free of corrosion or burrs. An antioxidant such as Burndy's Penatrox may be used on the terminal connections. Check and tighten all connections.

# POWER RESISTOR ENCLOSURES

Resistor enclosures (sometimes called racks and guards) are available from the resistor manufacturer to accommodate the various rated grid banks, edgewound banks, continuous strip banks and wirewound assemblies. These enclosures consist of mounting shelves to vertically stack the banks and protective screened covers made from expanded or perforated metal.

Galvanized enclosures will take the high temperatures but for appearance, high temperature paints are available at great cost. Very often different current range resistors are found in the same enclosure (due to the tapering current requirements) making universal “mill dimensions” mounting very desirable.

For outdoor installations, louvered covers are available. These enclosures are not as well ventilated as the screened and should be purchased one mounting space larger than needed. Leave this extra empty space at the top to exhaust the hot air out the top louvers in a sort of chimney effect. The heated air will produce a draft to efficiently remove heat from the enclosure. There are of course louvers near the bottom to let in the cooler air.