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LINE VOLTAGE REGULATION

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As automatic control equipment becomes more complex, it becomes more important for the development engineer to take advantage in the original design of the longer life, greater reliability, and higher accuracy which line-voltage regulation can provide.

Regulate for Life –The life of the cathode of a vacuum tube, for example, varies as the seventh power of the applied heater voltage. If the cathode is designed to operate with satisfactory emission over a $\pm 10\%$ heater voltage range, the life can be doubled by operation at the lower limit as compared to the design center, or increased by almost a factor of four over operation at the upper limit. However, if a tube is to be operated at its lower limit, it is important that the applied voltage be closely regulated so that it does not drop below the lower limit set by satisfactory emission. Extremely long life can be expected from some of the new computer-type tubes operated in this manner.[1]

All electric equipment will not give increased life at reduced operating voltage. Thyratrons often have very short life at low heater voltage and most motors will have excessive starting current and definitely shorter life when operated at reduced voltage. Too high a line voltage will provide excessive heating and reduced life. As a rough rule of thumb, heat will shorten equipment life by a factor of two for every 10°C. Thus, most equipment will have an optimum operating voltage. The realization of this fact, and the use of voltage regulation, can provide maximum life for control equipment.

Regulate for Reliability —Many factors contribute to the reliability of a piece of control equipment. One factor which every development engineer must consider is operating voltage range. While equipment often can be designed for operation over almost any voltage range, there is always an optimum voltage at which the probability of improper operation is a minimum. Furthermore, it is often possible to design a piece of equipment with greater reliability if the original design does not have to allow for a large operating voltage range.

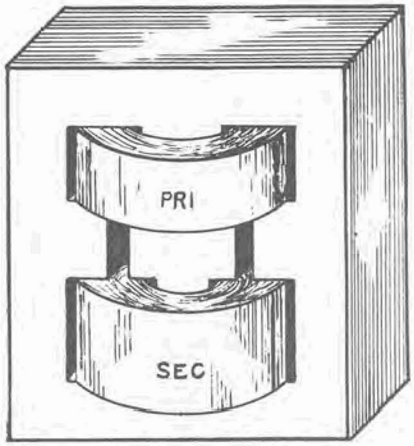

Figure 1. A resonant transformer winding and magnetic shunt change the coupling between the primary and secondary to reduce output voltage changes.

Another factor which affects reliability is operating temperature. Since heating is often proportional to the square of the applied voltage, excessive input voltage can produce considerable unnecessary heating. Thus, not only does increased voltage directly reduce the probability of proper operation, but it also produces additional heating which further reduces reliability.

Regulate for Accuracy — The accuracy of most equipment is affected to some degree by line-voltage changes. In some cases, this effect can be tolerated, in others the effect is minimized in the design by using feedback, cancellation schemes, or some other technique. Where high accuracy is required, voltage regulation is often the simplest and best technique. For the ultimate in performance, a combination of feedback, cancellation, and voltage regulation is often used.

Several techniques are available to accomplish line-voltage regulation. The most common methods use some form of saturable reactor, a servo-operated Variac,® or a vacuum-tube regulator. A thorough understanding of the characteristics of the various voltage regulators as well as the requirements of a particular automatic control equipment are necessary in order to choose the best type of voltage regulator for a particular application.

Constant Voltage Transformer —

The constant-voltage transformer, operates by having two windings, a primary and a secondary, separated by a magnetic shunt. The secondary winding is resonated with a capacitor so that the voltage across the winding is higher than would be calculated from the turns ratio between the windings. As this resonant voltage increases, the flux density in this part of the magnetic circuit increases forcing more of the flux which linked the primary and secondary coils through the magnetic shunt. This action tends to decrease the original increase in voltage across the resonant secondary winding. Thus, an output voltage taken across part of the resonant secondary will show considerably less variation than the input voltage. By adding a third winding, it is possible to cancel out the remaining output voltage variation to within about one per cent. Unfortunately, the saturation effect in the core causes as much as 20% distortion of the output voltage. A fourth winding is sometimes added to neutralize this distortion to less than 3%.[2]

If a constant-voltage transformer is overloaded, the output voltage will drop sharply. This provides a protective feature which will limit the

1 W. S. Bowie, "The Effects of Heater Cycling and Heater Voltage," 1956 I.R.E. Convention Record, Part 6.

2. See NOTE at end of article.

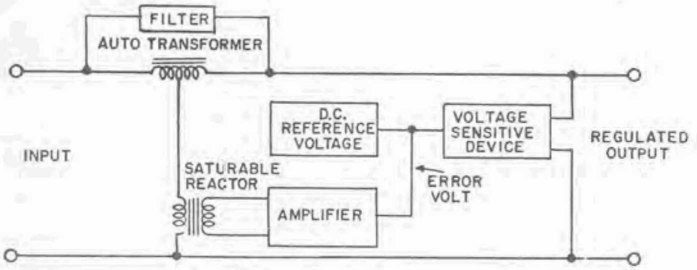

Figure 2. A Saturable Reactor is used as a variable impedance to control output voltage.

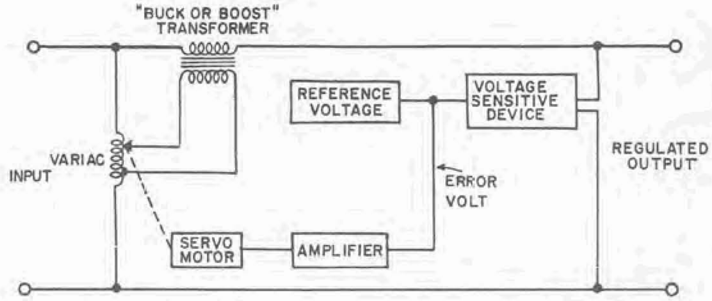

Figure 3. A Servo-operated Variac controls output voltage through a "buck or boost" transformer.

short-circuit current to about 200% of rated full load. For regulating motor loads, however, this overload characteristic requires that the regulator have a steady state rating equal to the peak starting current. This may require a regulator up to eight times larger than normal load would indicate. The efficiency of this type of regulator varies from about 50% in very small sizes to about 85% at 500 watts.

Thus, the constant-voltage transformer is advantageous in small sizes for supplying regulated voltage to a reasonably constant load where the power factor is high, frequency is constant, and harmonic distortion is not too important. This type of regulator should provide the best reliability and in small sizes the lowest cost.

Saturable Reactor Regulator —

The saturable reactor can also be used as a variable impedance between the input and the output to control the output voltage. The output is measured by some voltage-sensitive device and compared against a DC reference voltage. The difference between these voltages is the "error" voltage which is amplified to obtain sufficient current to control the saturable reactor. Since the AC impedance of the saturable reactor is a function of the DC current through the control winding, the voltage dropped across the autotransformer connected between input and output will change with the DC control current. This voltage change across the autotransformer will be in such a direction as to reduce any output voltage change and thus minimize the error voltage. The inherent distortion caused by the saturable reactor can be reduced by connecting a filter across the autotransformer. The filter will reduce the distortion below 3%.

By providing sufficient amplifier gain, the accuracy of the regulator can be made to approach the stability of the voltage-sensitive device and the voltage reference. Accuracy is about ±0.25% if the load power factor is between 0.5 lagging and 0.9 leading. The time required to correct an input voltage change is a function of the load, but is ordinarily between 3 and 10 cycles of the 60-cycle line frequency.

The reliability of this type of regulator depends almost completely upon the design of the electronic circuitry. While this can be very good, it will be poorer than the far simpler constant-voltage transformer type of regulator. Furthermore, the cost will be far greater in the small sizes since the electronic circuitry is such a large part of the cost. However, the performance is vastly superior.

This type of saturable reactor regulator is most useful for medium size loads (about 1 KVA) where the high speed of response is more important than the line-voltage distortion produced. The reliability is good as is the accuracy within its power factor restriction.

Servo-Operated Regulator —

If a servo-operated Variac and "buck-or-boost" transformer are substituted for the saturable reactor-controlled autotransformer in the regulating system just discussed, a different type regulator results with several unique characteristics. The output is measured by a voltage-sensitive device and compared against a reference voltage to obtain an "error" voltage. This "error" voltage is amplified and used to control a motor which repositions the Variac to reduce the original error. While this action is similar to that of the other type regulators, there are two important differences. First, the Variac is a completely linear device and effects a correction in the output voltage without introducing any distortion. Second, because of the effective integration in the motor, no error voltage is necessary to maintain a correction once it has been made. Note that in the other type regulators, an error voltage is necessary to maintain the required correction and, therefore, a certain error proportional to the correction required must always exist.

The servo-operated Variac line-voltage regulator possesses several other advantages. Above a few kilowatts, it is the least expensive type of regulator and is available in sizes up to 100 KVA. It not only provides control without introducing waveform distortion, but will operate with full accuracy at any load power factor. This type weighs considerably less per kilowatt output than other types, and is also the most efficient (over 98% at 5 KW). Accuracy is about ±1/4% and is completely independent of the applied load. Full accuracy is maintained even for large overloads which the regulator will tolerate for short periods of time. The speed of response is inherently slower than the saturable reactor and depends upon the magnitude of the correction required. A 1% voltage step will be corrected within eight cycles of a sixty-cycle voltage, whereas one second may be required to correct for a ten per cent voltage step. Thus, small transients and large, but slow, drifts will be corrected within a few cycles, but a large transient will require considerably longer. Reliability is good but because of the electronic circuitry, it is not equal to that of the simple constant-voltage transformer.

Electronic Regulator

The electronic line-voltage regulator is similar to the saturable reactor-type regulator except that an AC error voltage is obtained by comparing a portion of the output voltage against an AC reference voltage, and the amplified error voltage is fed back through a power amplifier and a linear transformer to correct the output. The all electronic regulator contains considerable circuitry which tends to reduce reliability and greatly increases the cost, but provides some features which cannot be matched by the other types. The most important feature is that the speed of response is essentially instantaneous. Thus, not only are fast transients reduced, but also distortion is reduced to that of the reference voltage. The residual distortion is about 0.3% and the accuracy is about ±1%.

This type is most useful in small sizes (about 1/2 KVA) where high speed of response and freedom from distortion are more important than cost, weight, efficiency, and reliability.

Type	Added Distortion	Accuracy	Approx. Weight (lbs/KVA)	Efficiency	Response Time (Cycles) 1% step	10% step	Freq. Range (Cycles)	External Field
Constant-Voltage Transformer	3% to 20%	±1%-±5%	70	50-90%	1.5	1.5	59.8-60.2	high
Saturable Reactor	3%	±0.25%	50	70-80%	3-10	3-10	55-65	low
Servo	None	±0.25%	10	98%	8	60	55-65	low
Electronic	Removes Distortion	±1%	100	40%	0.06	0.06	58-62	low

Figure 4. Summary of Regulator Characteristics.

NOTE

While the constant-voltage transformer is very reliable, and in small sizes quite inexpensive, the high-reluctance core produces a large external magnetic field and the resonant secondary causes the output to vary considerably with load power factor. A change of power factor from 100% to 90% can cause as much as a 4% change in output voltage. The output voltage will also change as much as 1.8% for every 1% change in line frequency.

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