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LOSSES IN ELECTRIC POWER SYSTEMS

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Introduction

This report concerns losses in power systems. The report was assembled by seven authors in EE 532 class at Purdue University in December, 1992. The work was part of a class project on losses.

All aspects of losses are discussed from the transmission system through utilization stages. High efficiency motors and lighting are also considered. The students participating in this project also videotaped presentations on power system losses.

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Chapter I Transmission Losses

T. D. Collins

The power system network that weaves about the United States is by far the largest interconnection of a dynamic system in existence to date. Like all other systems, no matter how carefully the system is designed, losses are present and must be modeled before an accurate representation of the system response can be calculated. Due to the size of the area that the power system serves, the majority of the system components are dedicated to power transmission. The focus of this paper is to describe the losses that occur in the transmission system, present component models, and investigate ways to reduce these losses.

I.1 System Parameters

When current flows in a transmission line, the characteristics exhibited are explained in terms of magnetic and electric field interaction. The phenomena that results from field interactions is represented by circuit elements or parameters. A transmission line consists of four parameters which directly affect its ability to transfer power efficiently.[3] These elements are combined to form an equivalent circuit representation of the transmission line which can be used to determine some of the transmission losses.

The parameter associated with the dielectric losses that occur is represented as a shunt conductance.[2] Conductance from line to line or a line to ground accounts for losses which occur due to the leakage current at the cable insulation and the insulators between overhead lines. The conductance of the line is affected by many unpredictable factors, such as atmospheric pressure, and is not uniformly distributed along the line.[4] The influence of these factors does not allow for accurate measurements of conductance values. Fortunately, the leakage in the overhead lines is negligible, even in detailed transient analysis. This fact allows this parameter to be completely neglected.

The primary source of losses incurred in a transmission system is in the resistance of the conductors. For a certain section of a line, the power dissipated in the form of useless heat as the current attempts to overcome the ohmic resistance of the line, and is directly proportional to the square of the rms current traveling through the line. It directly follows that the losses due to the line resistance can be substantially lowered by raising the transmission voltage level, but there is a limit at which the cost of the transformers and insulators will exceed the savings.[5]

The efficiency of a transmission line is defined as

$$\eta = \frac{P_R}{P_S} = \frac{P_R}{P_R + P_{Loss}} \qquad \text{(I.1)}$$

where P_R is the load power and P_{Loss} is the net sum of the power lost in the transmission system.[1]

As the transmission line dissipates power in the form of heat energy, the resistance value of the line changes. The line resistance will vary, subject to maximum and minimum constraints. in a linear fashion. If we let R_1 be the resistance at some temperature, T_1, and R_2 be the resistance at time T_2, then

$$R_2 = R_1 \cdot \left(\frac{235 + T_2}{235 + T_1} \right) \qquad \text{(I.2)}$$

if T1 and T2 are given in degrees Centigrade.[4]

The capacitive reactance of a transmission line comes about due to the interaction between the electric fields from conductor to conductor and from conductor to ground. The alternating voltages transmitted on the conductors causes the charge present at any point along the line to increase and decrease with the instantaneous changes in the voltages between conductors or the conductors and ground. This flow of charge is known as charging current and is present even when the transmission line is terminated by an open circuit.[6]

The alternating currents present in a transmission system are accompanied by alternating magnetic fields. The interaction of these magnetic fields between conductors in relative proximity creates a flux linkage. These changing magnetic fields induce voltages in parallel conductors which are equal to the time rate of change of the flux linkages of the line.[6] This voltage is also proportional to the time rate of change of the current flowing in the line. The constant of proportionality is termed as the inductance.

$$e = L\frac{di}{dt} \tag{I.3}$$

Due to the relative positioning of the lines, the mutual coupling will cause voltages to be induced. The induced voltage will add vectorally with the line voltages and cause the phases to become unbalanced. When a 3 phase set is unbalanced the lines do not equally share the current. Looking at only the simple resistive losses in the circuit, and recalling that the power loss is directly proportional to the square of the magnitude of the current flowing in the line, it is easy to see that the losses in one line will increase significantly more than the reduction of losses in the other lines. This suggests that a simple way to minimize the total I^2R losses is to maintain a balanced set of voltages. A second note is that the mutual coupling also increases the total line reactance. The line reactance further adds to the losses because it affects the power factor on that line.

The affect of this mutual coupling is often reduced by performing a transposition of the transmission lines at set intervals.[4] The transposition governs the relative positioning of the transmission lines. Each phase is allowed to occupy a position, relative to the other two phases, for only one third of a distance. Then the phases are rotated so their positions, relative to one another, change. By proper rotation of the lines, a net affect of significantly reducing the mutual inductance is realized. The actual phase transposition usually does not take place between the transmission towers. A certain safe distance must be maintained between the phases and, because of the difficulty in maintaining the required distances between the phases, transposition is most likely to take place at a substation.

1.2 Skin Effect

The internal flux of a conductor produces a phenomena known as skin effect. This flux consists of flux lines which are circular and concentric with the conductor surface.[1] This results in flux lines which only link a portion of the conductor's cross section. Therefore the central cross sections of the conductor have larger total flux linkages than the portions closer to the outside of the conductor. This means that a higher voltage will be induced, longitudinally, in the inside of the conductor than on the outside.[1] The total voltage gradient, however, must be the same in the conductor whether it is measured along the axis on the inside or along the outer surface.[1] Consequently, the current will not be uniformly distributed over the cross sectional area of the conductor. Instead the current density will be greater closer to the surface of the conductor. The ohmic voltage drop is directly proportional to the current density and is larger at the surface. This compensates for the opposite variation of induced voltage and maintains the uniformity of the total voltage change per unit length[1]. Since the ohmic and induced voltages are not in phase, not only will the magnitude of the current vary along the cross section of the conductor, but so will the phase angle of the current.[2] This phenomena is referred to as the skin effect. To account for this effect the line resistance value is multiplied by a constant based on the cross sectional area and the current rating of the conductor.

Skin depth is the measurement of the lateral penetration of the current within a conductor. As mentioned previously, the depth of penetration is determined by the internal flux arising from the current carried within a conductor. External flux linkages have no effect on the skin depth of a line. The skin depth of a copper conductor transmitting a 60 Hz. signal is approximately 0.75 cm.[2] As a result, not much of the current flows in the center of the conductor. This fact is a fortunate one because it allows the aluminum conductor, whose skin depth is root two times that of copper, transmission lines to be reinforced with a braided steel core without lowering the current carrying capacity.

1.3 Line Models

Due to the required distances between conductors, the loops formed between outgoing and return conductors are of considerable area. The changing flux in these loops will generate opposing voltages in the conductors which may be of considerable importance; particularly in regard to the voltage regulation of the line.[2] It is often more convenient to model the polyphase transmission system by a single phase representation and to calculate parameters as per mile quantities.[3] With the exception of detailed transient analysis and some calculations for long transmission lines, the models are based on a lumped parameter representation of the system.

I.3.1 Short Lines

A transmission line with length less than 50 miles is classified as being a short transmission line. When power is transmitted along a short transmission line the difference in conditions at the sending and receiving ends is due to the series impedance of the line. The impedance is that of a series connection between a resistive and an inductive element shown in Fig. I.1, where V_S and V_R are the sending and receiving line to neutral voltages and I_S an I_R are the sending and receiving currents. Since there are no shunt components

$$I_R = I_S \tag{I.4}$$

$$V_R = V_S - I_R / (R + jwL) \tag{I.5}$$

The induced voltage in the line is directly proportional to the current and will depend on the physical dimensions of the conductor. The value of this induced voltage, per mile, for a single conductor is given by

$$E_i = 0.00466 \times f \times I \times \log_{10}(1.285 \cdot \frac{d}{r}) \qquad (I.6)$$

where d is the distance between conductors, r is the radius of the conductor, I is the rms amplitude of the current, and f is the frequency of the current in hertz.[2]

The effect of the line impedance and the variation of the load power factor can best be seen in the load regulation of the line.

$$\text{Percent Regulation} = \frac{|V_{R,NL}| - |V_{R,FL}|}{V_{R,FL}} \text{ x } 100\% \qquad (I.7)$$

where $|V_{R,NL}|$ is the magnitude of the receiving end voltage at no load and $|V_{R,FL}|$ is the magnitude of the receiving end voltage at full load.[7] The regulation is greatest for a lagging power factor and least for a leading power factor.

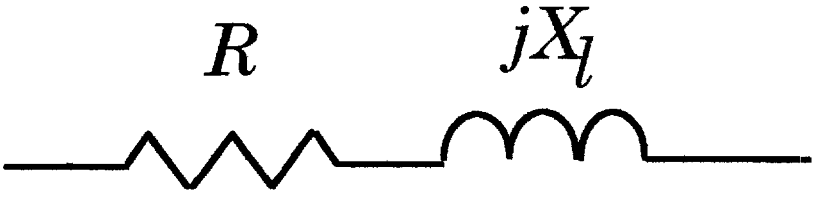

Fig I.1 Short transmission line model

I.3.2 Medium Lines

Lines of length between 50 and 150 miles are classified as medium length transmission lines. A shunt capacitance is added to the short line model to create the model for medium length lines. This extra element is needed due the increase in line length increases the capacitance, and its affects on the system become significant. The line capacitance between two parallel cylindrical conductors given in micro Farads, per mile, is

$$C = \frac{0.0194}{log_{10}\left(a + \sqrt{a^2 - 1}\right)} \qquad (I.8)$$

where a is the distance between the conductors divided by the diameter of the conductor.[2] Typically, the shunt admittance is divided equally and placed at either end of the line. This representation, shown in Fig. L2, is known as the nominal π equivalent circuit. By modeling the line in this manner, the receiving end voltages and currents can be obtained using the lines ABCD parameters from a two port network shown in Fig. 1.3.

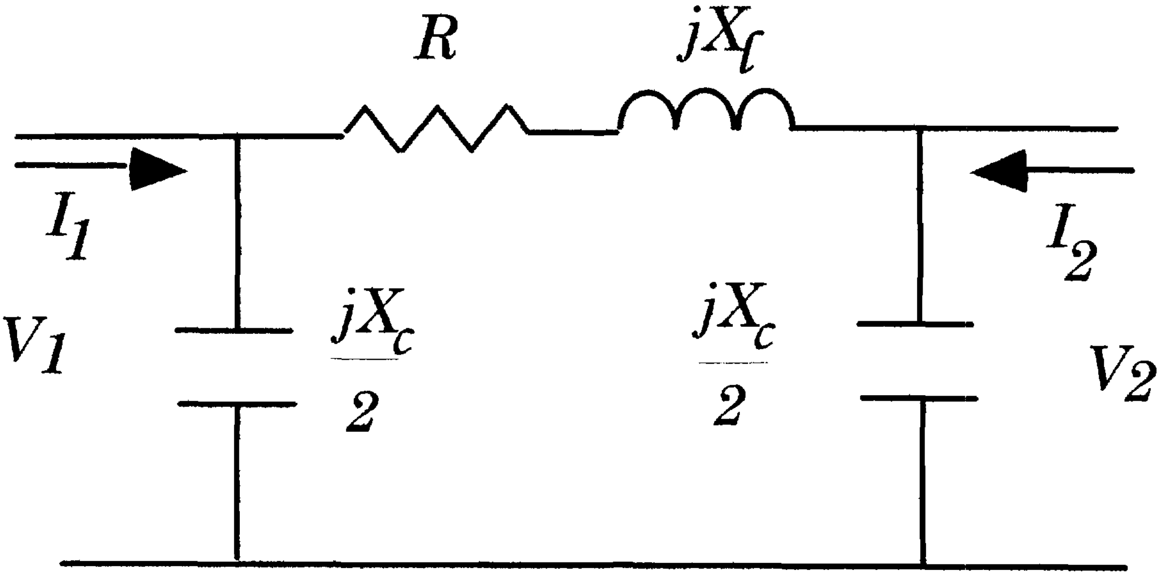

Fig. 1.2 Medium length transmission line model

$$A = D = \frac{ZY}{2} + 1$$

$$B = Z$$

$$C = Y\left(1 + \frac{ZY}{4}\right)$$

$$Y = \frac{1}{2jwC}$$

$$Z = r = jwL$$

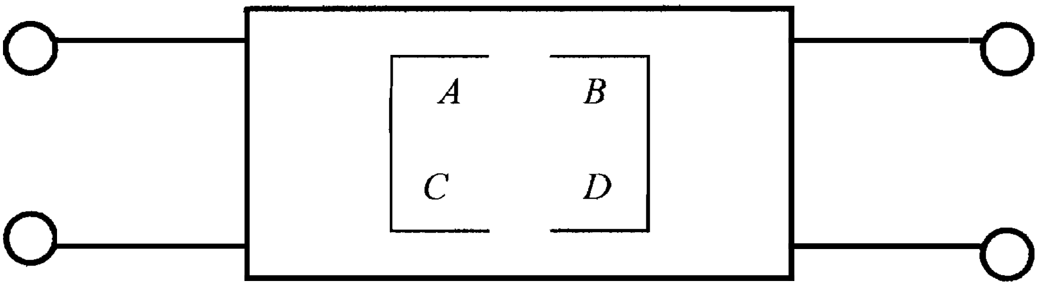

Fig. 1.3 Two port network and ABCD parameters

I.3.3 Long Lines

As transmission lines grow in length, the affect of the capacitance becomes more predominant. There is a sizable component of the total current which leads the voltage by 90 degrees, and the voltages induced by this current lags the phase current by 90 degrees and produces the charging current.[2] This reduces the necessary size of the sending voltage. The affect is most noticeable when the lines are subjected to very light loads. The long line model is similar to that of the medium line, The difference is that the long line is represented by distributed parameters instead of lumped parameters.[4]

1.4 Corona Loss

The air present in ow atmosphere is most commonly considered to be a good insulator, however, it is far from perfect. The imperfections result from the fact that there are always a small number of ions present due to various forms of radiation. When air is subject to an uniform electric field, the ions and electrons in the air are set in motion. By means of convection they maintain a small flow of current which, in most cases, can be neglected. However, once the electric field intensity reaches a value of 3000 kv/m, the ions accumulate enough energy between collisions with neutral molecules to allow then to tear an electron away from the free molecules.[2] This interaction adds a new electron and positive ion to the field. These new ions are accelerated by the force of the field and further ionize the intermediate air molecules. This process continues and an ion avalanche occurs. The field around a conductor is not uniform but has a peak value at the surface of the conductor[2]. Hence the value of the field drops of at a rate which is inversely proportional to the distance from the conductor.

The steep voltage gradient present at the conductor surface facilitates such ionization and serves as the catalyst to ion avalanche.[5] The ionization persists around the conductor and is accompanied by a glow from which it gets its name. The ions produced result in space charges which are being moved by the alternating field. The energy that is expended in the moving of these ions is removed form the transmission line itself, so it is considered to be a transmission loss.[2] The rate at which ionization occurs is not uniform, but rather occur as fluctuations which produce sudden changes in the electric field and result in radio interference.

1.5 Transformer Losses.

In practice, the most effective way to reduce losses incurred in the transmission network has been through the use of transformers. Transmission lines serving as links to an area with a modest load demand would experience extremely high losses if they were required to carry the full load current. To prevent this from occurring , the line voltage is stepped up by a large ratio, N, while the line current is simultaneously stepped down by a factor of 1/N. This allows the transmission lines to carry the large amount of power while greatly reducing the system losses. The I^2R losses alone are decreased by a factor inversely proportional to N^2. However, transformers do have losses of their own. The three mechanisms by which transformers exhibit losses are through hysteresis, I^2R, and eddy currents. The I^2R losses occur in the windings and the others occur in the core material.

The winding, or copper, loss is determined in a straight fonward manner from the resistance of the winding and is expressed as

$$P = RI^2{}_{rms} \tag{I.9}$$

The core loss encountered is a transformer is expressed in terms of hysteresis and eddy currents.[8] These two have a net loss that may be approximated as varying linearly with the fiequency, f, and having a nonlinear dependence on the flux intensity, B, of the core material.[2]

$$P_{core} \propto f \cdot B^{(1.6\text{-}2.0)} \tag{I.10}$$

Hysteresis loss results from the unrecoverable energy expended to rotate the polarization of the core's magnetic material. The energy loss per unit cycle is expressed as the area enclosed by the hysteresis loop.[8]

$$E = \oint dW_m = \oint H \cdot dB \tag{I.11}$$

The total hysteresis loss is the product of this area, the core volume, and the frequency. Eddy current loss is simply expressed as the I^2R loss due to the currents induced in the magnetic material.

Transformers consists of two or more windings that are coupled by a shared magnetic circuit, or core, which provides a low reluctance path to link common flux. In order for the windings to be coupled magnetically, the B field must be created by one winding and linked by the other. The main component of the core which accomplishes the link is the magnetizing inductance which is modeled by a large inductor.[7] Unfortunately, not all of the flux produced in one winding is successfully linked to the others. Some of the flux leaks from the core and has a return path through the air. This effect of the imperfect coupling is modeled as a small series inductor known as the leakage inductance.

Many design methodologies have been formulated in an attempt to reduce the leakage inductance. By placing the windings directly over the top of one another, all of the flux in the core is linked by both windings. However, there still exists a small amount of flux generated in the outer winding that is not linked by the inner windings. Another approach is to recognize that the leakage flux increases with the winding thickness. Windings that are long and slim yield lower values for leakage inductance than do windings that are short and fat. Since the leakage flux has a return path that is external to the core, it results in electromagnetic interf'erence. To minimize EMI, a one-foil wide winding is short circuited and placed around the entire magnetic circuit. The leakage flux induces currents in this shorted winding which create an opposing flux and reduce the EMI.

The resultant mutual flux, linking the windings, can be separated into two components. The load component is described as the current in one windings that would exactly cancel out the mmf of the other windings. The exciting current is the additional current needed to produce the resultant mutual flux.[7] Although the exciting current is non sinusoidal, it can be represented as a magnetizing component, I_m, and a core loss component I_c. The exciting current is modeled as a shunt conductance G_m in parallel with the magnetizing inductive reactance X_m. The model for a typical transformer is shown below.[7]

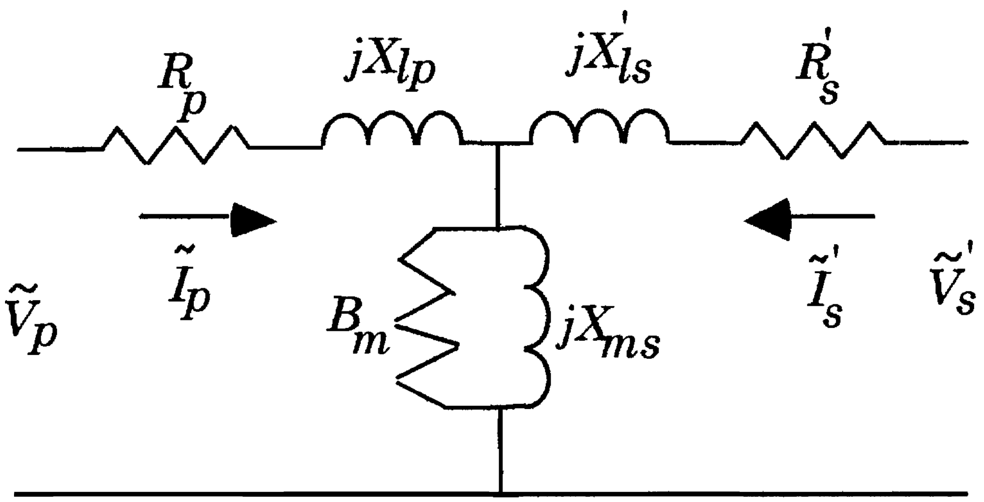

Fig. 1.4 Power transformer model

1.6 Summary

By understanding the interactions of magnetic and electric fields, equivalent circuit models can be constructed to describe the phenomena which takes place within a transmission line. An analysis of these: models will quantify some of the losses within a transmission line, which consist of 3 to 5 percent of the load. Depending on the level of accuracy desired and the length of the line, models of varying complexity may be used to describe the system. The use of transformers in the transmission system greatly reduces the I^2R losses, but the transformer does bring some additional elements into the loss equations.

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Chapter II Losses in HVDC Transmission Systems

S. P. Hoffman

II.1 Introduction

High voltage direct current, or HVDC transmission systems are used primarily to move large amounts of power over very long distances or through submarine cables, and for an asynchronous tie between two interconnected power systems. One of the biggest advantages of this type of transmission system is that the losses in the system are very low and large amounts of power can be transmitted. For example, the Intermountain Power Project is a ±500kV 1600MW HVDC transmission system which transmits the full output of two generating units in Utah to load centers in Southern California [8]. This paper will present a brief introduction to HVDC transmission systems. The losses that occur in each component of the system will also be determined. A typical HVDC transmission system is shown in Fig. No. II. 1 [12].

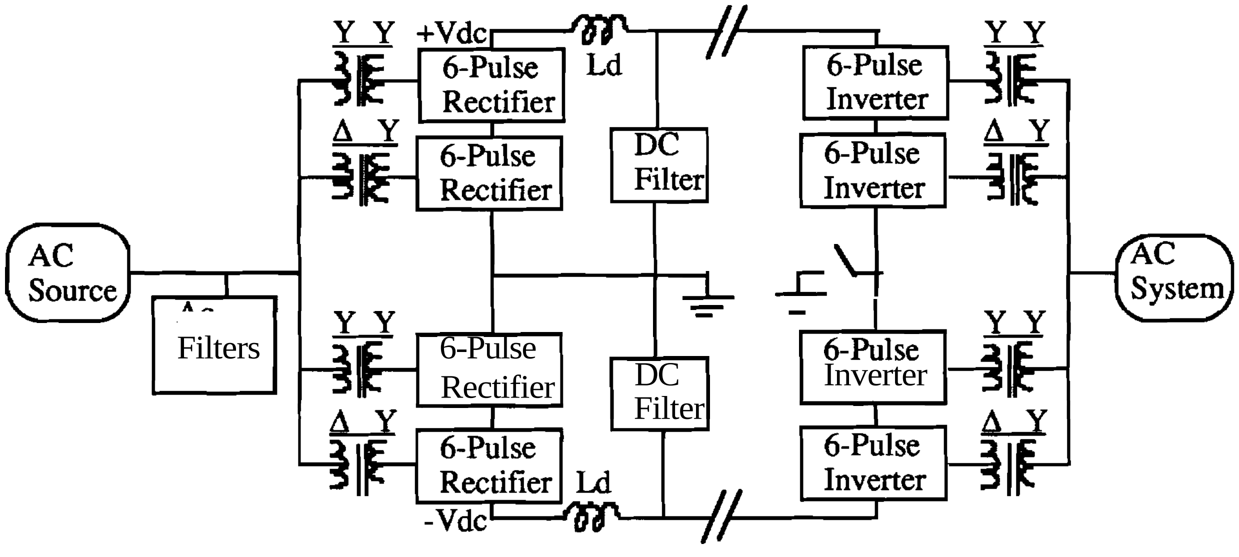

Fig. No. II. 1
Bipolar, 12-pulse HVDC Transmission System

11.2 Brief History of HVDC Transmission Systems

In the early days of electrical generation, from 1880 to 1910, dc motors were used to generate dc voltage. One of the first transmission systems was the Thury System. This system was constructed by attaching several dc generators in series to produce the high voltage needed for transmission and used dc motors connected in series on the receiving end. The series connected dc motors were connected to low voltage dc or ac generators to provide the low voltage needed for distribution. One such system was constructed between Moutiers and Lyons, France and attained a voltage of 57.6kV at 75 Amps for an initial power rating of 4.3MW, which was later increased to 19.3MW at 125kV with the addition of another generating station [1].

The initially popular and prevalent dc transmission systems were replaced by ac transmission systems with the development of the transformer, polyphase circuits, and the induction motor. The transformer was used to step up the voltage of the ac waveforms for transmission over the polyphase (two or usually three phase) lines. After the voltage was reduced to distribution levels by another transformer the ac voltage was used directly to power induction motors. The rugged, inexpensive, and reliable induction motors required an alternating voltage source. The dc motors used in the Thury system were not able to produce the amount of power that was needed as the power system grew and had several other disadvantages, such as the cost of maintaining the motors and a large number of commutators in series. These combined factors hastened the replacement of dc by ac for electrical power generation, transmission, distribution, and use. Although there were several experimental HV dc links in the 30's and 40's the first commercial HV dc transmission system was installed between the island of Grotland and the mainland of Sweden. This system used one single underwater cable and used the sea for a return path for the electricity. Today there are more than 20 HVDC transmission systems worldwide. The installed capacity of HVDC transmission systems has reached 45 GW.

II.3 Advantages of HVDC Transmission Systems

Power transfer over long distances is determined in HV ac lines by the electrical angle between the sending and receiving end and reactive compensation (a shunt capacitor) is often needed to keep the voltage within an acceptable range as the load on the line changes. A very long ac line also faces stability problems if the electrical length of the line approaches 900. Thus in ac transmission systems the amount of power that flows over the line is determined by the system voltages and can only be determined by performing a power flow study for the entire ac system.

A dc transmission system offers several distinct advantages over ac transmission systems. The amount of power that can be transmitted with dc is only limited by the amount of heating that the line can tolerate without melting or sagging. The amount of current that flows through the line causes heating of the line due to the by I^2R power losses. Since the frequency of the dc is zero, there are no limitations on the length of the line and shunt capacitors are not needed with dc as they are with ac. The amount of real and reactive power that flows over a dc transmission link can be directly controlled by the way in which the valves (switches) in the converters are turned on. This is an advantage for transmission links between interconnected systems in that the power that flows can be scheduled and directly controlled instead of flowing on the ac lines that present the lowest resistance path. Since the ac voltage at the receiving end of the dc transmission line is reconstructed from dc, it can be at a completely different frequency or at a frequency that is the same but is not in synchronism with the source voltage. This feature allows the asynchronous connection of two power networks by a dc transmission line, which is not possible with an ac connection. For underwater HVDC transmission systems reactive compenstion is not needed between the lines since the frequency of dc is zero. HVDC transmission systems can use the ground for the return path since large amounts of dc current can be passed through the ground with very low resistance because the dc flows through a large cross-sectional area of the earth. With a bipolar line ground return is not used since the plus and minus voltages cancel out at the inverters.

HVDC transmission systems are clearly the best choice for three applications. They are used for bulk power transfers over a long distance on overhead lines, underwater transmission links, underground urban transmission links, and for an asynchronous tie between two interconnected power systems. HVDC overhead lines are narrower than ac lines so more power can be transmitted over the same right-of-way [10]. An asynchronous tie would typically have the rectifier and inverter in the same location and is used because the flow of real and reactive power can be directly controlled. The HVDC system is often used to inject or absorb reactive power to provide VAR compensation to the ac network, which is used to increase the power flow and for voltage regulation in ac lines [11]. The two systems do not need to operate in synchronism and can even operate at different frequencies. All of these systems have the same components and differ only in the distance between the converter stations and the design and installation of the cable used for transmission.

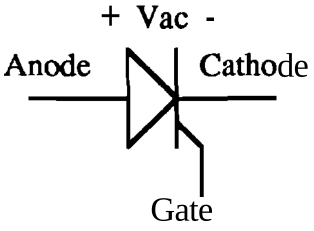

Figure No. 11. 2
Thyristor Circuit Symbol

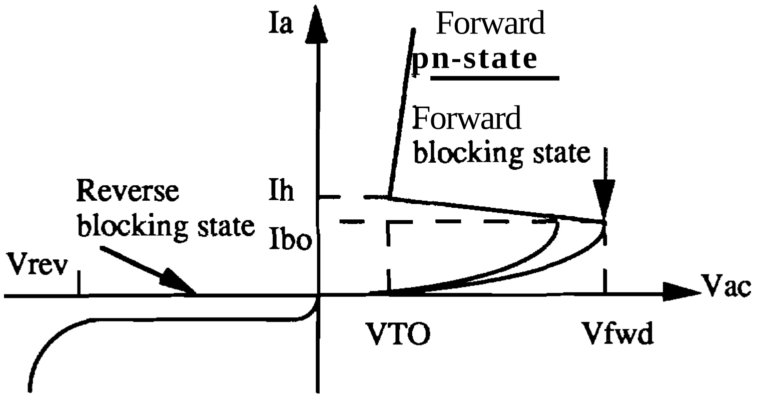

Figure No. 11. 3
Thyristor Current vs. Voltage

Ibo = forward break-over current
Ih = forward minimum current
VTO = forward on-state voltage drop
Vfwd= forward breakdown voltage
Vrev = reverse breakdown voltage

11.4 Thyristor Valve Operating Characteristics

The first valves that were used for HV dc converters were mercury arc valves. These were used successfully in all of the HVDC transmission systems prior to the 1970's. Mercury arc valves have been replaced by silicon diodes with control electrodes, called thyristors or silicon controlled rectifiers (SCRs). The circuit symbol for the thyristor is shown above in Figure No. II. 2. The thyristor has the same basic operating characteristics as a mercury arc valve. The graph of thyristor current versus voltage is shown above in Figure No. II. 3. It should be noted that this graph is not to scale since the forward voltage drop VTO is about 1.5 volts, the forward breakdown voltage is typically equal to **5kV,** and the reverse breakdown voltage is approximately equal to -5kV for HVDC thyristors.

11.5 Converter Circuit

To build a dc transmission system a method is needed to convert back and forth between the ac and dc voltages. A rectifier is used to convert ac to dc and an inverter is used to convert the dc back into ac. These circuits are collectively called converters. The actual circuit topology of a rectifier and an inverter is the same and the only difference is the method in which the valves are turned on.

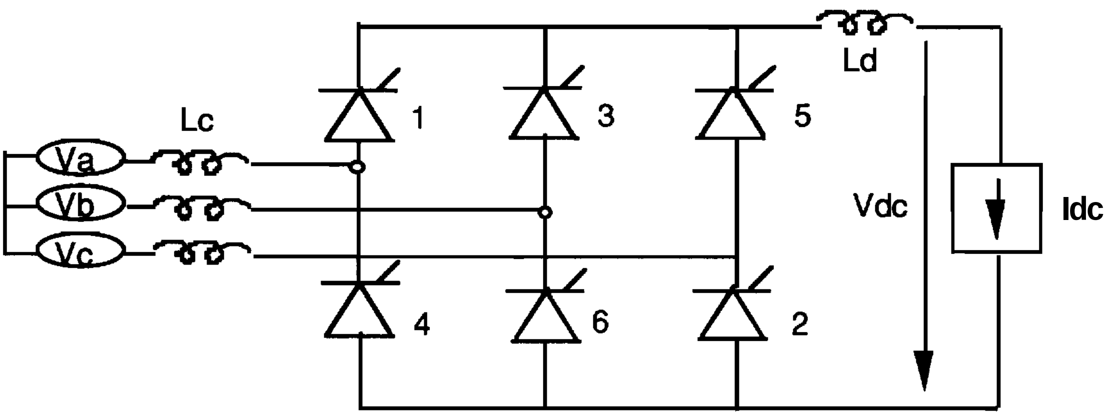

Figure No. II. 4 Three Phase 6-pulse Converter Circuit

Lc = inductance of the converter transformer
Ld = dc smoothing inductor
Va = Vmax * Cos(2*pi*time)
Vb = Vmax * Cos(2*pi*time - 2*pi/3)
Vc = Vmax * Cos(2*pi*time + 2*pi/3)
Vdc= output dc voltage

Time Interval	Valve Conducting
$0<t+a<60$	1,6
$60<t+a<120$	1,2
$120<t+a<180$	2,3
$180<t+a<240$	3,4
$240<t+a<300$	4,5
$300<t+a<360$	5.6

The converter circuit that is used to convert from three phase ac to dc is shown in Fig. No. II. 4. The 6 switches that make the operation of this circuit possible are commonly called valves. The valves are the six numbered components shown in Fig. No. II. 4. These valves ideally conduct in the forward direction (anode to cathode) and block current from flowing in the reverse direction, similar to the operation of a diode. These valves operate differently than a diode in that these valves block current in the forward direction until a voltage is applied to the gate control terminal. The valve will continue to conduct until the voltage across the valve becomes negative. The valve can be thought of as a switch that can be turned on only when there is forward voltage across the device and can be turned off only when the voltage across the device becomes negative. The valves in the converter circuit shown in Fig. No. II. 4 must be controlled to fire at a certain order for the device to operate properly. Va, Vb, and Vc represent a balanced, three-phase, abc sequence voltage set.

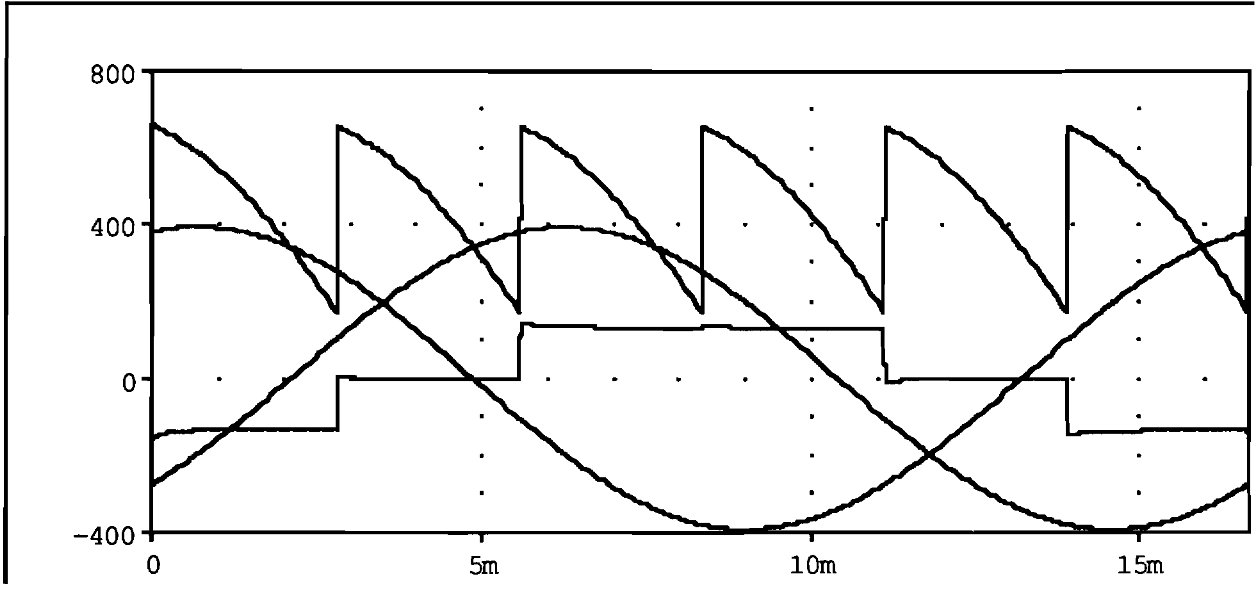

Figure No. II. 5, Va, Vc, Vd, and Ia versus time

Since valve one can only be turned on when the voltage across the valve is positive there is only 180° when it is possible to turn on a valve. The waveform shown in Fig. No. 5 shows Va, Vc, the output voltage Vd, and the input current Ia for a delay angle of 45 degrees for one period, which is 16.7 milliseconds. This plot ignores the effect of the commutation angle on the output dc voltage. As can be seen from the diagram valve one can only be turned on when Va is greater than Vc, which is from 3.5ms until 12ms. The delay angle, a, is defined as the delay from when the valve can be turned on until it is actually turned on by the control circuit. If the delay angle is zero the output dc voltage is a positive maximum and decreases as the delay angle increases. With a delay angle of 90 degrees the average value of the output dc waveform is zero volts. As the delay angle is increased further the output dc voltage actually becomes negative and is a maximum when the delay angle equals 180 degrees. The output voltage is given by Vd = $V_{do}*\cos(a)$, where V_{do} is the maximum dc voltage output [1]. An inverter uses a firing angle close to 1800 to convert the dc voltage on the receiving end back into ac. Since the rectifier and inverter only differ in the way in which the valves are fired the delay angle can be changed to reverse the direction of power flow on the dc line. This flexibility of controlling the flow of power is one of the distinct advantages of dc transmission systems.

The turn-off time of the valves was disregarded in the input current Ia and output voltage Vd shown in Fig. No. II. 5. It takes several electrical degrees for the current flow to be transferred from, for example, valve one to valve three. This time is called the commutation angle, u, and the resulting current waveform is shown in Fig. No. II. 6. Since both valves are conducting for a brief period of time Va and Vb are shorted together and the resulting dc voltage waveform is the average of Va and Vb. This has the effect of reducing the output dc voltage from Vb to (Va+Vb)/2 during the commutation angle.

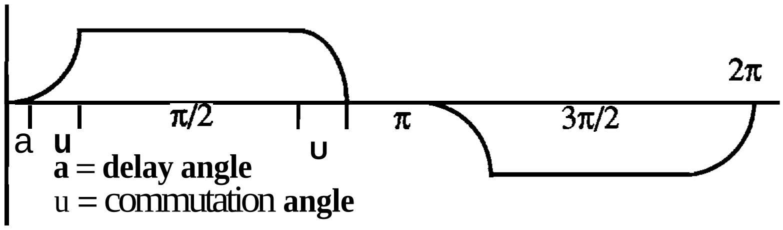

Figure No. II. 6 Single Phase Line Current Ia versus Time

II. 6 Rectifier Characteristic Harmonics

As can be seen from Fig. No. II. 5 the "dc" voltage produced by the rectifier is actually a complex, periodic waveform with a large average value equal to Vd. The output waveform shown in Fig. No. II. 5 neglects the effect of the commutation angle on the dc output voltage, which makes the output waveform Vd and even more complicated waveform. A large smoothing reactor (inductor) Ld is used at the output of the rectifier so the current harmonics on the dc line are considered to be small. The frequency of the output dc waveform is six times the frequency of the 60 hz input voltage. This is why this rectifier is refered to as a six-pulse bridge. The voltage harmonics on the dc side of the rectifier are calculated using Fourier analysis and have components at six times the fundamental frequency of 60 hz. These voltage harmonics are removed by harmonic filters that are tuned to the harmonic frequency. These harmonic filters introduce further losses to the dc system. Ideally all harmonics other than multiples of 6 times the fundamental are zero but in practice there are components at the uncharacteristic frequencies because of differences in the ignition angle a of each valve. The dc filters are as shown in Fig. No. II. 7 and this filter is tuned to the sixth harmonic for a six-pulse bridge and to the 12th harmonic for a 12-pulse bridge [9].

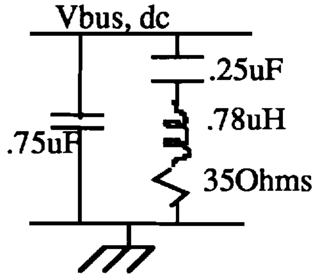

Figure No. II. 7
Dc Harmonic Filter

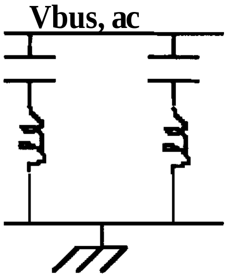

Figure No. II. 8
Ac Harmonic Filter

The input ac current is not sinusoidal and therefore has a large harmonic content. The ac input current for phase a is shown in Fig. No. II. 6 and is obviously not sinusoidal. When Fourier analysis is performed on this waveform the harmonic components are found to exist at the 5th, 7th, 11th, 13th, ... harmonics for a six-pulse bridge. For the 12-pulse bridge system described in Fig. No. II. 1 two 6-pulse converters are used with source voltages that differ by 30 electrical degrees to eleminate the 5th and the 7th harmonic. The 300 voltage shift is produced by the wye to delta wound converter transformer.

The magnitude of each individual current harmonic is inversely proportional to the harmonic order. For example if the magnitude of the fundamental component of current is one, the magnitude of the fifth harmonic would be 0.2 and would be 1/7 for the seventh harmonic. This gives a total harmonic distortion (THD) for the current equal to 0.29 for a six-pulse bridge and 0.15 for a 12-pulse bridge. Total harmonic distortion is defined as the square root of the sum of the per unit harmonic components excluding the fundamental. The IEEE-519 Recommended Practices and Requirements for Harmonic Control in Electric Power recommends that the maximum THD for a very strong ac system be no greater than 20 percent [7]. Since the value calculated above is greater than this value ac filters are needed to remove the harmonic currents. The ac filter is tuned to reduce the 11th and 13th harmonic for a 12-pulse system and the basic circuit diagram is shown in Fig. No. 8 [9]. There is some power loss in the ac and dc filters due to the I^2R copper loss in the inductor windings.

11.7 Losses in Converter Transformers

Although the harmonic current components are reduced by the ac filters, they are not completely eliminated. The remaining harmonic currents must flow through the converter transformers and are injected into the ac network. These transformers are between the ac network and the converter circuits and are represented in Fig. No. 4 as an equivalent inductance. A transformer will not be able to carry as much current with harmonics as it can current that is a pure sinusoid. Power transformers are designed to carry sinusoidal, 60 hertz currents.

The IEEE Recommended Practice for Establishing Transformer Capability when supplying Nonsinusoidal Load Currents describes the recommended decrease in total transformer load current due to the harmonic content of the current flowing through the device [4]. The flow of harmonic currents through the transformer causes extra heating due to the I^2R losses and the eddy current that is caused by the higher-frequency current. Converter transformers are specifically designed so that they can carry the currents demanded by the converter [5]. The harmonic content of the load current increased the transformer load losses by 89kW to 729kW for a 262 MVA converter transformer [6]. This gives a converter transformer efficiency equal to 0.28%. The Intermountain Power Project's converter transformers have an efficiency equal to 0.32% [8]. Since the load loss represents energy that is converted into heat in the transformer it is apparent why fans and air-cooled fins are used to cool a power transformer.

11.8 Thyristor Valve Installation

A thyristor valve package was installed in 1985 in the Sylrnar Converter Station of the Pacific DC Intertie [2]. The thyristor valves used in this HVDC system are able to block 4700 volts in the forward direction and 5200 volts in the reverse direction, with a current rating of 2000 amps. Since the operating voltage of a typical HVDC transmission system is plus and minus 400 to 500 thousand Volts each of the six valves represented in the converter circuit (Fig. No. II. 4) are actually a series and parallel connection of the individual silicon thyristors. The series connection is needed so that each valve will not have to block more than its rated voltage in the forward and reverse directions. The parallel connections are used so that each individual thyristor valve will not be forced to carry more than its rated current.

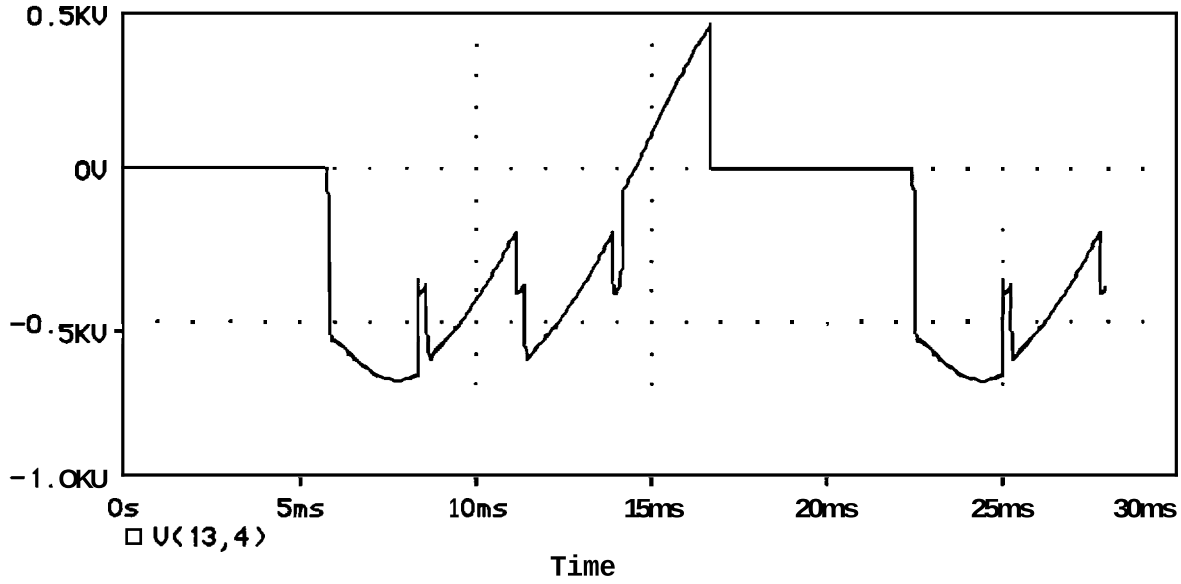

Fig. No. II. 9 Voltage Across Valve

Snubber circuits are used to limit sharp changes in voltage in the forward or reverse direction from damaging the SCR thyristor. These snubber circuits are series connections of a resistor and capacitor across each thyristor. A saturable reactor (inductor) is connected in series with the valve to limit the change in current flowing through the valve with respect to time. There are some losses in the RC circuit due to the resistor. The inductor introduces further losses since the iron core is magnetized and demagnetized during each cycle as the current through the thyristor is turned off and on. The voltage across each valve is shown in Fig. No. 9, where the zero volts portion of the graph represents the on-time of the thyristor. The loss in the snubber circuits can be calculated by determining the voltage waveform across the entire valve and calculating the power that is absorbed by the resistor [13]. This method is not necessarily appropriate since each thyristor valve is a series connection of several thyristors and smoothing reactors, each having their own snubber circuits. The turn-on time of each valve is slightly different so it cannot be assumed that the voltage across the entire valve divides evenly between each thyristor. Since the heat produced by the snubber circuits is removed by the same cooling system that cools the valves, it is difficult to determine the exact percentage of the losses that is due to the snubber circuits.

The diameter of the silicon in the SCRs is 77-mm. Since the device is relatively large the amount of time required to turn on the device can be substantial and the valves are specifically designed with large gate area for fast turn-on times. The valves are light activated and are fired by light from a cesium vapor flash lamp conducted over fiber-optic cables. The use of light triggering eliminates the need for the high voltage signal that would otherwise be needed to turn on the thyristor valves. The light actually turns on a separate, smaller light triggered thyristor which in turn activates the power thyristor. The forward voltage drop for one individual thyristor at rated current of 2000 amps is 1.6 volts.[2]

11.9 Thyristor Valve Losses and Cooling System

The power loss in the thyristor itself is very small and is of the order of hundreds of watts to thousands of watts per device, depending on the application. The power that is lost in the valves can be attributed to the forward voltage drop and the forward on state resistance according to the formula given in Equation II. 1 [3]

Equation II. 1 $P{,}th = (VTO + rd*Id)*Id/3$

VTO = forward voltage drop across thyristor
rd = forward dc resistance of thyristor
Id = dc current through thyristor

Since most of the power lost in the converter is converted to heat a method is needed to cool the valve package. In the Sylmar Convertor station a two-phase cooling system is used to cool the valve unit [2]. This system uses Refrigerent 113 which is partially boiled in heat sinks located on each side of the valve and is subsequently cooled by an air-cooled water and glycol heat exchanger unit. Each individual valve is clamped to two heat sinks. The most unusual requirement for this valve cooling system is that the Refrigerant 113 used does not conduct electricity and is heated at high positive and negative electrical potential by the valves and snubber circuits. The refrigerant is cooled at ground potential by separate water-glycol line which is subsequently cooled by an air exchange unit. Since the cooling system is critical to the operation of the converter station it is designed with multiple sensors and controllers so that it can still operate or can be safely shut down if a sensor or a pump malfunctions. At rated load this cooling system rejects 105kW per valve group. The operating losses for this system were calculated to be 630kW for the six-pulse bridge. With a power rating of 267MW for this system the calculated losses as a percent of the power is 0.236% [2]. The appeal of dc transmission systems becomes clear when one considers the high efficiency of the converter station.

11.10 HVDC Transmission Line Design and Losses

HVDC transmission lines can be either bipolar or monopolar. A monopolar line has one insulated wire and uses either the ground or a separate neutral wire for the return path of electricity. Ground return can be used because the dc resistance of the earth in most locations and in water is nearly equal to zero. A bipolar line uses two insulated transmission lines which are held at a potential of typically plus and minus 500 thousand volts, respectively. In the bipolar operating mode the ground return current is zero since the voltage at the inverter sums to zero. If one line of a bipolar system develops a fault, the system can still deliver one-half of the rated power by operating in the monopolar mode with ground return. The losses on the line are due to the I^2R losses and to the corona losses. The corona power losses are given as 4.2kW/km for a ±490 kV HVDC system [10]. This would amount to a loss of 2.1MW for a 500km line. The Intermountain Power Project HVDC line is rated at 1800MW so this would give a corona loss approximately equal to 0.13%. The copper losses would be equal to the I^2R loss and this value depends upon the amount of current that flows through the line and the resistance of the line. With dc the current flows evenly throughout a cross-section of the cable. With ac the current tends to have a greater current density towards the edges of the cable, which is called the skin effect. Thus the dc current can be greater than the ac current in the same cable. A small amount of power is also radiated in the radio noise and audible noise frequencies.

II. 11 Conclusions

High Voltage Direct Current transmission systems are used primarily for asynchronous ties between two interconnected power systems, to transmit large amounts of power over long distances on overhead lines, and for underwater power links. HVDC has the advantage over ac in that the flow of real and reactive power can be directly controlled. The losses in HVDC systems are very low and are summarized as follows. One should note that these loss percentages should be taken as approximate because these numbers were determined for components in different systems. The actual circuit losses depend on the transmission system and its operating point. The converter transformer used in HVDC systems experiences the normal operating loss due to the flow of sinusoidal current and has additional losses due to the harmonic currents that flow through the device. The transformer losses were found to be about 0.25%. The losses in the snubber circuits and the thyristor valves are best measured by determining the amount of heat that is removed by the cooling system. This was found to be about 0.24% but the heat that is lost to the ambient is not easily measured and is also part of converter losses. The losses in the line are due to the corona losses and to the copper losses. The corona losses were found to equal about 0.13%, although this percentage varies with different line voltage levels. The copper losses are proportional to the square of the line current and depend on the resistance of the transmission line.

When the loss percentages due to each component are added up the total losses come out to 1.5% to 4%. It must be emphasized again that this value was found by adding up losses of components that were operating in different systems and at different operating points. The total losses for an HVDC system depend upon the system. For example, the line losses for a 800 mile HVDC link would be much greater than the line losses for a back-to-back link. Direct measurement of converter station losses is not possible because the losses are less than one percent, which is below range of accuracy in the measuring meters [3]. To quote the discussion in [13] by H. P. Lips and G.

Weissenberger, 'It should be kept in mind that loss considerations, though important, must range second after the objective to control thyristor stress for all operating conditions, parameter spread, and component failure scenarios.' This provides the best indication that although systems are designed to be as efficient as possible, the real engineering work and study goes into ensuring that the system will operate reliably and correctly for all possible normal and abnormal operating conditions. Fortunately HVDC system losses are very low and this approach produces a successful power transmission system.

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Chapter III Losses in Power Distribution Systems

D. J. Gotham

III.1 Introduction

After electric power is generated, it is sent through the transmission lines to the many distribution circuits that the utility operates. The purpose of the distribution system is to take that power from the transmission system and deliver it to the consumers to serve their needs. However, a significant portion of the power that a utility generates is lost in the distribution process. These losses occur in numerous small components in the distribution system, such as transformers and distribution lines. Due to the lower power level of these components, the losses inherent in each component are lower than those in comparable components of the transmission system. While each of these components may have relatively small losses, the large number of components involved makes it important to examine the losses in the distribution system. These losses typically account for approximately four percent of the total system load. [1]

There are two major sources of losses in power distribution systems. These are the transformers and power lines. Additionally, there are two major types of losses that occur in these components. These losses are often referred to as core losses and copper, or I^2R, losses. Core losses in transformers account for the majority of losses at low power levels. As load increases, the copper losses become more significant, until they are approximately equal to the core losses at peak load. [1]

The economic implications of these losses are far reaching. In addition to the excess fuel cost needed to cover the lost energy, added generating capacity may be needed. Also, the power lost in the distribution system must still be transmitted through the transmission system which further adds to the loss in that system. It is very important for electric power suppliers to consider these losses and reduce them wherever practical.

III.2 Losses in Distribution Lines

One of the major sources of losses in the distribution system is the power lines which connect the substation to the loads. Virtually all real power that is lost in the distribution system is due to copper losses. Since these losses are a function of the square of the current flow through the line, it should be obvious that the losses in distribution lines are larger at high power levels than they are at lower levels.

Since power loss in the distribution lines can be considered to be entirely due to copper losses, it can be calculated using Equation III.1.

$$P=I^2R \qquad \text{Eqn III.1}$$

From this, it is apparent that anything that changes either current or line resistance will affect the amount of power lost in the line.

The primary determining factor for the magnitude of line current is the amount of real and reactive power loading at the end of the line. As the power that is transmitted along the line increases, the current flow in the line becomes larger. Another factor which affects the level of current flow is the operating voltage of the line. For a given real and reactive power load level, S, a high voltage line will have a lower current than a low voltage line. This can be seen from Equation III.2.

$$S=VI \qquad \text{Eqn III.2}$$

Therefore, for a given power level, the higher voltage line will have lower copper losses.

Another factor which can result in higher line losses is unbalanced loading. If one of the phases is loaded more heavily than the others, the loss will be larger than it would have been in the balanced load case. This is due to the squaring of the current in Equation III.1. For instance, if one line carries twice the current of the other two and all other factors are kept constant, an increase in copper loss of 12.5% occurs compared to the balanced load case.

While the current level has the biggest effect on line loss, the resistance of the line cannot be neglected. The line resistance depends on many factors, including the length of the line, the effective cross-sectional area, and the resistivity of the metal of which the line is made. The resistance is inversely proportional to the cross-sectional area and directly proportional to both the length and resistivity. This is shown in Equation III.3 below, where R is the resistance, p is the resistivity, L is the length of the line, and A is the effective cross-sectional area.

$$R = \rho \frac{L}{A} \qquad \text{Eqn 111.3}$$

Therefore, a long line will have a higher resistance and larger losses than a short line with the same current flow. Similarly, a large conductor size results in a smaller resistance and lower losses than a small conductor.

The resistivity is determined by the material of which the line is constructed and the temperature of the material. A better conducting material will result in lower resistivity and lower losses. The resistivity of the metal in the line will be affected by the temperature. As the temperature of the metal increases, the line resistance will also increase, causing higher copper losses in the distribution line. The resistivity of copper and aluminum can be calculated from Equation III.4.

$$\rho_1 = \rho_2 \frac{T_2 - T_0}{T_1 - T_0} \qquad \text{Eqn 111.4}$$

The letter rho, p, is the resistivity at a specific temperature. It is equal to 2.83×10^{-8} ohm meters for aluminum and 1.77×10^{-8} ohm meters for copper at a temperature of 20°C. T_0 is a reference temperature and is equal to 228°C for aluminum and 241°C for copper. ρ_1 and ρ_2 are the resistivities at temperatures T_1 and T_2 respectively.[2]

III.3 Losses in Distribution Transformers

While losses in distribution lines are virtually all due to copper losses, transformer losses occur due to both copper and core losses. The core losses are made up of eddy current and hysteresis losses. The copper losses in transformers are essentially the same as those in the power distribution lines.

The copper losses in a transformer are smaller in magnitude than the core losses. These losses occur in the form of heat produced by the current, both primary and secondary, through the windings of the transformer. Like the copper loss in the distribution line, it is calculated using the I^2R relationship of Equation III.1. Any factor which affects either current or winding resistance will also affect the amount of copper loss in the transformer.

An increase in loading, either real or reactive, will result in an increase in current flow and a correspondingly greater amount of loss in the transformer. Additionally, an unbalanced system load will increase transformer loss due to the squared current relationship. The winding resistance also has an effect on the amount of copper loss and is mainly determined by the total length of the wire used, as well as the size of the wire. The temperature of the winding will affect the resistivity of the wire, therefore affecting the overall resistance and the copper loss. Since all but the smallest distribution transformers have some type of cooling system, such as immersion in oil, the temperature effect on losses is usually minimal.

The core loss in a transformer is usually larger in magnitude than the copper loss. It is made up of eddy current losses, which are due to magnetically induced currents in the core, and hysteresis losses, which occur because of the less than perfect permeability of the core material. These losses are relatively constant for an energized transformer and can be considered to be independent of the transformer load. Transformer core losses have been modeled in various ways, usually as a resistance in parallel with the transformer's magnetizing reactance. [2] [3] [4]

Since the core loss is relatively independent of loading, the most important factor when considering core loss is the manufacture of the core. The physical construction of the core has serious consequences on the amount of core loss occurring in the transformer. For instance, eddy currents are greatly reduced by using laminated pieces to construct the core. These thin sheets are oriented along the path of travel of the magnetic flux and restrict the amount of induced currents that occur. [3]

The hysteresis loss occurs in the transformer core due to the energy required to provide the magnetic field in the core as the direction of magnetic flux alternates with the alternating current wave form. This energy is transformed into heat. Hysteresis loss can be reduced by the use of higher quality materials in the core which have better magnetic permeability. Many advanced core materials have been developed recently with claims of core loss reductions in the range of 50 % and above. [5] [6]

A final aspect of the distribution system that increases losses in the transformers is the presence of harmonics in the system. The harmonic currents only cause a small increase in copper losses throughout the system. However, the high frequency harmonic voltages can cause large core losses in the transformer. Frequently, utilities are forced to use an oversized transformer to compensate when a large harmonic presence is indicated. The increased skin effect of larger conductors combined with the high frequency harmonics can result in even greater losses. [7]

III.4 Methods of Lowering Distribution System Losses

Since distribution losses cost the utilities a sizable amount of profit, it is necessary to examine the various methods of reducing these losses. While many ways of lowering losses can be used on existing systems, other methods are easiest to use during the initial design and installation of a new distribution system. An example of one of these methods is to carefully select the location of the substation so as to minimize the needed length of distribution lines. Another way is to use as high as voltage as is practical for the lines to limit the current in the lines and transformer windings. Also, the higher resistivity of aluminum means it will have larger losses than an equivalent copper distribution line. Therefore, copper should be used on lines where losses are abnormally high. Other methods, such as high efficiency transformers and shunt capacitor banks, may be easier to install during initial construction than they would be on an existing system.

High efficiency transformers, which use new core types, are beginning to see widespread use in the United States. One example of a more efficient core is one that uses amorphous metal. Amorphous metal is formed by rapidly cooling liquid metal. Approximately 60,000 to 70,000 amorphous metal transformers are currently in use, mostly in the United States. While amorphous metal transformers cost 25 to 50% more than silicon iron transformers, they also claim 60 to 70% less losses. Therefore, utilities with high energy costs or those facing new plant construction would do well to consider them. [6]

Perhaps the most common method of reducing system losses is the use of shunt capacitor banks. Capacitors are used to compensate for reactive loads in order to provide a highly resistive total load and a near unity power factor. Hence there is less current flow in the line and lower losses. The capacitors are strategically placed to provide the best voltage support and current reduction. In one case, the use of shunt capacitors reduced distribution system losses by approximately 20 %. However, care must be used when choosing the placement of the capacitor banks. In the above example, the loss reduction was calculated to be less than 5% when the capacitors were equally distributed throughout the system. [1] [8]

Another method of lowering system losses is by reducing the amount of harmonics present in the system. This can be accomplished by placing filters at each load that produces major non sinusoidal signals. However, these filters cost money and have inherent losses due to the imperfect nature of the components which limit the loss reduction that is achieved.

Utilities may also reduce losses that occur in the distribution system by ensuring that the load is well balanced on all three phases. This will keep the copper losses in the lines and transformers to a minimum.

A final method of reducing distribution system losses is demand-side management (DSM). With DSM, a utility reduces the system loading, especially at peak periods, by turning off certain loads or providing incentives for efficiency. Overall load is reduced by encouraging improved efficiency by consumers with such things as rebates for high efficiency motors, refrigerators, and lighting. Peak load can be reduced by direct load control of such items as air conditioners, hot water heaters, and some industrial loads. DSM has an added benefit in loss reduction because the primary load reduction occurs at peak loading when system copper losses are greatest.

III.5 Conclusions

The losses that occur in distribution systems are large enough to make efforts to reduce them worthwhile. Core losses in transformers, which account for the majority of distribution losses at low power, can be reduced by improved core materials and by reducing harmonics. Copper losses, which become more important at higher power levels, can be reduced by a number of means, including increased use of copper distribution lines, shunt compensation, and demand-side management.

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Chapter N: Uninterruptible Power Supplies

N.1 Introduction

Despite the best efforts of the electric power utilities, electric power disruptions still occur. The length of the disruptions may range from much less than one cycle to several days. Depending on the application that is consuming the power, the disturbance may be nothing more than a minor inconvenience or a major disaster. There are many different applications that may require emergency or back up power, ranging from the lighting of exit ways to the powering of critical environmental or computer systems. Depending on the duration of the disturbance and the criticality of the load, different systems have been developed to meet the needs of the load. [1] Since the protection system is itself an added electrical load, except during a disturbance, its efficiency is a topic of interest. When the protection system deals with large amounts of power, the cost of operating an in-efficient system could be very large. To minimize the operating costs, an efficient protection system is desired.

This chapter will examine some aspects of efficiency for systems suitable for disturbances that are measured in minutes or less. This is reasonable since approximately 99% of all disturbances are in this category [1] and the backup supplies for the longer term durations typically consists of an engine and a generator and is similar to the normal AC power supply. The systems that are designed to replace or supplement the normal AC power supply during a disturbance are commonly called uninterruptible power supplies (UPSs).

Efficiency is simply defined as the ratio of the output power to the input power. [2] In many complex systems, including UPSs, the efficiency is a function of many different variables such as the power range at which the system is operating. This fact makes it difficult to correctly compare efficiency figures from different sources for two reasons. The first reason is that the tests may not have occurred at the same percent loading and the second reason is that the input and output points in the system may not always be defined in the same location for every system. Therefore to prevent the comparison between the proverbial apples and oranges, various UPS topologies and techniques to improve their efficiency will be discussed in leu of a discussion of the most efficient system.

IV.2 Basic topologies of UPSs

The UPS functions by providing stored energy to replace the source energy that is lost during a disturbance.[1] There are two basic topologies used to solve this problem, the on-line and the off-line topologies. [3] Both topologies are very similar as is shown by figures IV.1 and IV.2. Each

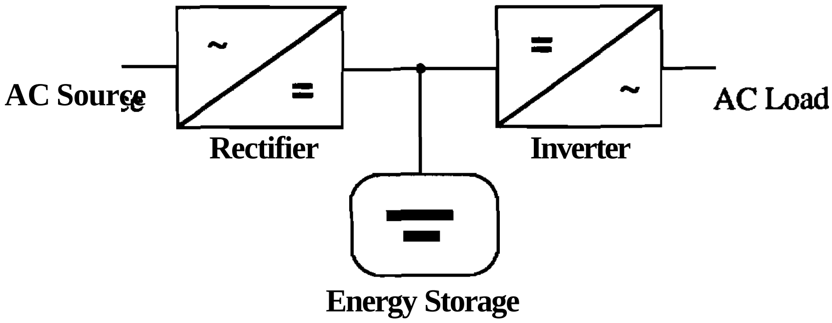


Figure IV.1 UPS on-line topology

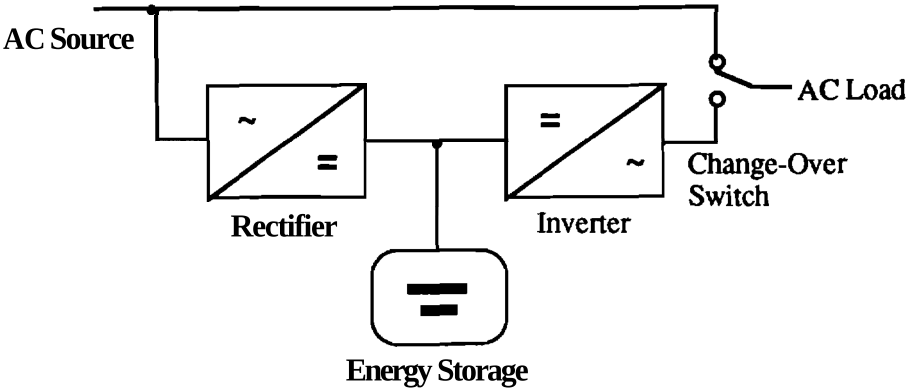


Figure IV.2 UPS off-line topology

topology has a converter from the AC power to an energy storage medium, the energy storage medium and another converter from the medium to the output AC power. In the off-line UPS, the load is only powered from the converters during the disturbance, while the on-line UPS continuously powers the load from the converters. Some on-line UPSs have a "by-pass" switch installed to allow them to operate off-line for service of the unit or to satisfy an excessive power demand from the load.

The efficiency of the off-line UPS is in general higher than the efficiency of the on-line UPS. This can be seen as follows. Assume that the UPS system is a linear system with respect to energy and that two UPS systems, an off-line system and on-line system, have identical converters and energy storage media. Initially assume that there is no load connected to either UPS. Now connect both units to a power source. Each will consume an identical amount of energy charging the storage media and a certain amount of energy will be lost in the media through self discharge. Thus far, both units have identical efficiencies. Now disconnect the source and then connect the UPSs to identical loads. Each UPS will lose identical amounts of energy in the media discharge and in the output conversion. Again, both units have the same efficiency. Finally, restore the AC source and leave the load connected. Both UPSs will have similar losses from the media self discharge, but for the off-line UPS this is the only loss. The on-line UPS has losses in the the second converter. Therefore, the on-line UPS will have a lower efficiency in this mode of operation than the off-line unit. This final mode is the typical case and it is here that the off-line UPS is more efficient. (The observant reader will note that energy absorbed by the recharging batteries after the source was restored was not mentioned. This energy will be reclaimed minus the discharge and converter losses when the source is interrupted and therefore is not considered a loss.)

In most applications, the UPS is used more as a power conditioner than as a backup energy source because 99% of the disturbances do not require the back up of a battery bank. [1] Since the on-line UPS is able to perform this task, and the interruption of the power while the off-line unit switches on may be longer than the disturbance itself, the on-line UPS is the more commonly chosen topology for critical applications.

IV.3 The energy media

There are many possible forms of energy storage media including electrochemical batteries, inertial batteries or compressed gasses. The electrochemical and inertial media are the most commonly implemented in UPSs. The inertial battery (henceforth referred to simply as a flywheel) stores its energy in the kinetic energy of the rotating mass. [1]

The electrochemical battery system that is in most common use is the lead acid battery. [4] Most large power UPSs (greater than 100 kVA) use vented lead acid batteries, while the medium power (between 10 and 100 kVA) and low power (under 10 kVA) units use sealed lead acid batteries. [5]

The recent push for electric vehicles has created several other emerging technologies for secondary or rechargeable battery systems. [6] Some examples of these systems include Sodium/Sulfur, Lithium monosulfide, Zinc/Bromide, Nickel/Zinc, Nickel metal hydride and Nickel/Iron. One of theses systems may someday be used to replace the lead acid battery in UPS systems, since the new batteries have comparable to or higher efficiencies than the lead acid system.

The battery discharge and charging efficiency is affected by its rate of discharge or charge (among several other variables). The efficiency is inversely related to the battery's discharge rate.[4] Table IV.1 compares the discharge efficiency of various battery systems at different discharge rates. The hour rate entry indicates the discharge rate. This number represents the number of hours at a constant current are required to completely discharge the battery.[6]

While the nickel cadmium batteries have excellent discharge efficiencies, they also have very large self discharge rates and low energy capacity as compared to the lead acid batteries.[4] These reasons strongly contribute to the choice of lead acid over nickel cadmium.

The flywheel storage units consist of a motor, a generator and a rotating mass. Depending on the design of the motor and generator, the

Table N.1 a comparison of battery discharge efficiencies [4] [6]

Battery System	Discharge η	Hour Rate	Self Discharge
Lead Acid	100%	20HR	3%/month
	93%	10HR	
	85%	5HR	
	60%	1HR	
Nickel/cadmium	105%	20HR	20-30%/month
	102%	10HR	
	100%	5HR	
	90%	1HR	
Sodium/sulfur	91%	3HR	N/A
Lithium/ monosulfide	88%	3HR	N/A
Zinc/bromide	81%	3HR	N/A
Nickel/zinc	75%	3HR	N/A
Nickel/metal-hydride	74-80%	3HR	N/A
Nickel/iron	58%	3HR	N/A

N/A-not available

flywheel formed by the combined mass of the two rotors and its normal rotational velocity often produces enough momentum to provide sufficient protection for disturbances of up to 100 ms (six cycles at 60Hz). [7] The energy capacity and protection time can be increased by increasing the flywheel mass.

A prototype 5kVA, 3Φ UPS has been developed in Japan using a flywheel storage unit.[8] The high tension steel flywheel is enclosed in an evacuated chamber to prevent windage losses. The chamber's pressure of 10^{-3} to 10^{-4} Pascals is maintained by a getter vacuum pump. To reduce frictional losses in the bearings, special magnetic and oil bearings are used to prevent any mechanical contact between the rotor and the stator. The flywheel is an induction machine with its rotor windings on the outside of the stator windings (The stator windings are located at the central axis of the flywheel.). The developed unit has an energy capacity of 330 Wh when the flywheel's rotational velocity is decreased from its rated speed of 15,000 rpm to 7,500 rpm. The charging and discharging efficiency is 89% as compared to a battery efficiency of 40% (Note: these values were provided by [8] and both the hour rate and type of battery system are not mentioned.). The flywheel can be charged within one to two minutes without a lowering of its efficiency. The developed UPS can provide rated power for 60 seconds.

A similar flywheel system has been proposed for electrical vehicle use.[6] This proposed system would use special, light, composite materials and an extremely high rotational velocity of approximately 95,000 rpm to store its rated 1kWh of energy.

IV.4 Converter topologies

There are two basic topologies that are used in the converters: static and rotary.[9] The static converters use combinations of solid state switches and control logic to perform the power conversion between the AC supply or load and the DC battery. Rotary converters use a coupled motor and generator combination to perform the conversion.

IV.4.1 Static conveters

The static converters perform two different functions: conversion of AC to DC and conversion of DC to AC. Some converter topologies are able to perform both functions, while others only perform one of the two functions. A rectifier is a converter that performs AC to DC conversion and an inverter is a converter that performs DC to AC conversion.[10] The topology of the converters is greatly influenced by the relationship of the AC and DC voltages and if galvanic isolation is present between the AC source and the critical load.

Rectifiers

There are numerous variations on the rectifier topology. Usually the converter is either a controlled rectifier bridge or an uncontrolled bridge rectifier followed by a DC to DC converter.[10] If isolation is desired at this stage, a transformer may be included prior to the rectifier bridge.[15]

One implementation developed to have high efficiency and a unity power factor uses a Switch Mode Rectifier (SMR).[11] The SMR consists of MOSFET switches and diodes arranged in a bridge configuration as shown in figure IV.3.

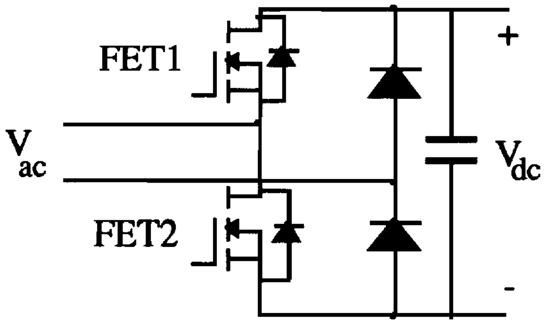


Figure IV.3 switch mode rectifier topology[11]

With careful control of the switching times, the DC voltage can be stabilized to a desired value and the AC current wave form is made to be sinusoidal and in phase with the voltage wave form. The developed SMR has a peak efficiency of 97% when operated at 50% load. At 75% rated load, the SMR has an efficiency of 96% and at rated load, an efficiency of 95%. For a detailed discussion of rectifiers and their operation, the reader is referred to [10].

When a transformer is included in the converter to provide isolation or AC voltage changes, care must be made in its specification since a poor choice may end up with low efficiency, a high transformer temperature and reduced converter life.[15] In one documented case by [15], changes of as much as +/- 2% were observed in the efficiency of identical UPS systems. These changes were incorrectly blamed on variations in the transformer manufacture. A later analysis of the problem revealed that the input line voltage had changed, causing a change in the firing angle of the rectifier to maintain a constant DC output voltage. This change in the firing angle, changed the power factor of the rectifier and hence the actual loading of the transformer. This placed the improperly chosen transformer in an in-efficient operating region and caused the observed change in efficiency for the whole unit.

Inverters

Inverter topologies have many variations. Only three types of switched converters will be mentioned in this chapter. The types are pulse width modulation converters, resonant converters and switched capacitor converters. It is possible to build an inverter where the switches operate in the linear region. While this linear inverter could produce a pure sinusoidal output, its efficiency would be limited to 50%. This problem is one reason why this topology is not in common use. When the switches are operated outside of the linear region, converters with a much higher efficiency can be obtained.

Pulse width modulation inverters

One popular mode of inverter operation is that of High Frequency Pulse Width Modulation (HF-PWM).[2][11][12][13][14] In this mode, a high frequency square wave is pulse width modulated to produce sinusoidal wave forms. By varying the duty cycle of the switches and low pass filtering their output, a sinusoidal output can be produced as shown in figure IV.4.[10] The switches may be controlled with a microprocessor to reduce the converter weight, size and control circuit power.[12] If isolation is desired, a transformer may be included between the switch output and the output low pass filter.[13] One topology causes the PWM inverter to generate a high frequency sinusoid, passes this sinusoid through a transformer and then uses a cycloconverter (an AC to AC converter

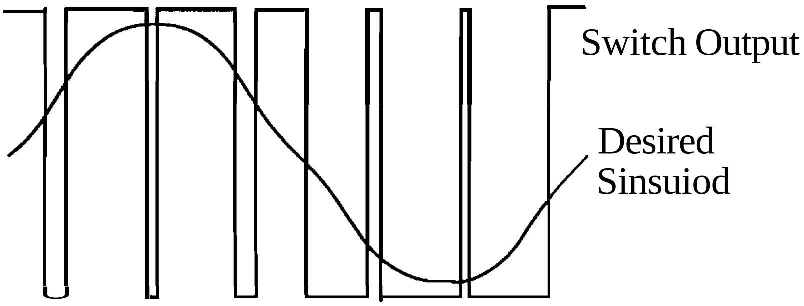


Figure IV.4 pulse width modulation[10]

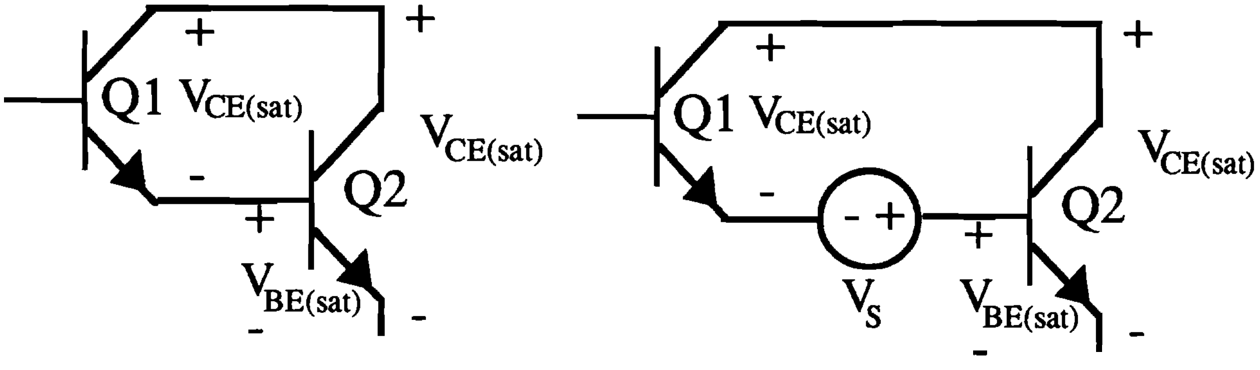
topology[10]) to produce the final 50/60Hz output. This technique reduces the size of the transformer, but lowers the efficiency of the overall converter because of the addition of the cycloconverter stage.[13] As mentioned earlier, proper choice of the transformer must be made to maintain a high converter efficiency.

Several techniques have been proposed to boost the efficiency for the HF-PWM topology. Four different techniques will be examined in this chapter: the judicious choice of the device selected for the switches,[2] lossless snubber networks,[8][13] special device driver circuits[14] and a resonant converter to produce zero voltage intervals for the PWM switches to operate.[16][20]

In [2], a Static Induction Transistor (SIT) or power JFET[10] was used in place of a comparable bipolar device. The developed SIT converter had an efficiency of 93% as compared to the bipolar's efficiency of 91% when both were operated under similar conditions (full rated power of 1kVA, 60Hz output frequency, PWM modulation of 80% and switching frequencies of 20kHz for the SIT and 15kHz for the bipolar). It was also found that the PWM modulation rate affects the efficiency of the converter. Higher modulation rates, produce higher efficiencies.

Snubber networks are required to protect the switch devices during the switching operation by limiting the large overcurrents and large overvoltages and by shaping the device wave forms so that the device stresses are reduced.[10] Often the snubbers consist of a resistor / capacitor (RC) circuit. The resistor's presence in the circuit introduces losses for every switching cycle. Special snubber networks have been made up of switches, inductors and capacitors. They are developed in [8] and [13] to reduce the switching losses by collecting the transient energy that is usually dissipated by the RC snubber and re-injecting it back into the DC link's capacitor. Both techniques reported significant improvements in converter efficiency.

The "on" voltage drop across a switch becomes especially important when a high powered inverter is driven from a low voltage DC battery. The corresponding high currents can cause high switch losses. To correct this problem, the use of low loss base drive circuitry has been demonstrated in [14] for use with Darlington configured bipolar transistors. The technique consists of inserting a small voltage in series with the emmiter of the first transistor and the base of the second transistor. This voltage, V_S, is set to cancel out the $V_{BE(sat)}$ of the second transistor and therefore reducing the $V_{CE(sat)}$ of the effective transistor. See figure IV.5. This circuit increased the total system efficiency from 94% to 97% when operated at 75% of rated load.



Uncompensated Darlington

Compensated Darlington

Figure IV.5 normal and improved Darlington drive circuit[14]

The switching losses are very small when the switching instant occurs during a zero-voltage and/or zero-current interval.[20] These intervals can be created for the PWM switches to operate in through the use of a resonant circuit. The resonant converter creates an inductor / capacitor (LC) resonance that is synchronized with the PWM switching frequency.[16] The developed converters of [16] and [20] showed decreased switching losses of almost one order of magnitude in per unit when a resonant circuit preceded the PWM circuit.

Resonant inverters

Another popular mode for inverter operation is the resonant converter.[16][17][18][19] This topology usually generates some form of an inductor / capacitor (LC) resonance and uses the zero voltage or current instances to change the state of the converter switches. There are four basic topologies for resonant converters;[10] however, all of the examples presented here will be variations on a single topology, the load resonant converter. A complete introductory coverage of resonant converters is available in [10].

Some techniques to improve the efficiency of the load resonant converters include selecting an optimum combination of turn-off methods for gate turn-off thyristors (GTO),[17] synchronizing the cycloconverter switches to the zero current points,[18] and using asymmetrical resonant bridges when the sub-topology is that of a series/parallel bridge converter.[19]

When GTO's are used in the parallel resonant converter circuits (a sub-classification of load resonant converters), they can be operated in one of two different modes: the load is fed either with a leading or a lagging current. When the load current is leading, the devices are turned off with "natural commutation" using the same process that occurs in normal thyristors; however, when the load current is lagging, the devices are turned off with forced commutation, *i.e.* gate action.[17] It was found by [17] that the optimum mode of operation is a partial natural commutation followed by a forced commutation. This produces a maximum switching frequency and the minimum switch loss.

Resonant converters sometimes use a high frequency link for similar reasons that the PWM converters use this type of link. Improvements in the efficiency of this converter can be made when the cycloconverter switches are synchronized with the resonant current zero crossing intervals.[18] This synchronization can be difficult to perform in real time when the states of the switches must also be calculated, so [18] has incorporated a state estimator to determine, in real time, the proper switch states for each switching instant.

Series/parallel resonant converters consist of two resonant bridge inverters whose outputs are added vectorally by an output transformer.[19] By adjusting the phase shift between the two bridges, the output can be controlled. Usually the two bridges are used are symmetrical, but this choice causes unequal sharing of load currents between the two bridges. The unequal currents are caused by the difference in power factors that the bridges are presented with. The power factor difference arises from the vectoral addition of the bridge outputs. This problem is corrected in [19] by compensating each bridge so that they both have a near unity power factor. The compensated, asymmetrical bridges improve the current sharing by a factor of 3 and also have a higher efficiency due to the lower stresses on the devices.

Switched capacitor inverter

A newly developed inverter topology that can be used for UPSs is the switched capacitor power converter (SCPC).[21] This topology develops the output AC using only capacitors and switches. Currently SCPCs are in common use for low power DC-DC voltage step down converters, but [21] has developed techniques to allow the use of SCPCs in inverters. The SCPC works by sequentially charging several series capacitors from the DC source and taking the AC output from across the capacitor stack. The sequential charging of the capacitors creates a staircase waveform which can be further filtered if desired. Extra switches are used to reverse the polarity of the stack for the negative half cycle and produce the maximum negative peak. The 1kW developed unit used eight capacitors and had an average step size of 20 volts.

IV.4.2 Rotary converters

The rotary converter consists of a motor driving an generator. Typically the motor is a DC machine and the generator is an AC machine. The rotary converters typically have an efficiency of 96-97% and these losses are due to the mechanical friction and wind resistance.[9] Often the motor and generator are separate and distinct machines that are mechanically coupled;[1] however, there are some implementations that have combined both machines into a single unit.[7] This unit, called a unitized motor generator (UMG), consists of a single rotor with two field and two damper windings and a single stator with the motor and generator windings. The brushless excited synchronous motor is powered from a standard thyristor inverter. The rotor's magnetic field from the motor action interacts with the stator's generator windings to produce the desired AC output. The developed UPS has a total efficiency at rated load of 94% when operated from line power and a total efficiency of 93%

when operated from batteries. As is demonstrated with the UMG, the UPS topologies are often very blurred since this converter uses both a static converter and the rotary machine.

IV.5 Commercial comparison

Based on the discussions of the different components for the UPS system, a crude estimation of the efficiency of a hypothetical system might be made. Choose this system to be an on-line UPS and assume that the disturbances are short enough that the energy storage media losses can be ignored. If a conservative efficiency of 92% for both converters is assumed, then the on-line efficiency of the hypothetical UPS would be 85% ($\eta_{total}=\eta_{rectifier} \bullet \eta_{inverter}$). This estimation agrees with the stated efficiencies of commercial UPS systems. A deluxe UPS model line with the power range of 500VA to 3.1kVA has a stated on-line efficiency of 81-92%.[22]

IV.6 Conclusions

Uninterruptible power supplies are a very important solution to the problem of providing consistent power to critical loads. The increased use of them to protect the number of critical loads makes their efficiency a concern. To improve the efficiency of the UPS system, there are many different topologies and techniques that are used. In many cases, the developed UPS is a hybrid of different topologies. This chapter has discussed several of these topologies and techniques. Regardless of the method or topology implemented, the developed efficiencies are usually fairly high, ranging in the 80-90% range for the different components. The component with the lowest efficiency is the battery.

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Chapter V Efficiency of lighting systems

David Karipides

V.1 Introduction

The incandescent lamp that Thomas Edison perfected in the late 1800's is today the main source of illumination in our homes. While there have been improvements it its design such as the tungsten filament and various fill gasses, the basic design has changed very little in over 100 years. Although the efficiency of the incandescent lamp is the worst of all commercial light sources, the quality of the light produced in terms of its color balance is better than that produced by most of today's high-efficiency lamps.

Since lighting is an important part of architectural design, the styles of the time play an important part in the success of a new lighting system. Until recently, the use of some high efficiency discharge lamps was considered undesirable in indoor spaces. These efficient lamps were mainly used to illuminate factory floors and parking lots due to their poor color rendition until it was found that using a combination of various types of lamps could be used to produce a pleasant white light suitable for normal working conditions.

Designing lighting systems with the sole purpose of maximizing efficiency is unrealistic. If this were the main goal, a light source would be designed so that all of the light it generates is in the yellow-green region of the spectrum where our eyes are most sensitive. However, living in a world where color is indiscernible and everything appears a shade of yellow-green would rapidly become unnerving. For this reason, the spectral distribution of a lamp must be a major factor in its design or it will never be accepted as a useful source of light.

V.2 Lighting terminology

To discuss the various types of lamps, one must first define some terms which describe the physics of light and color. The human eye is sensitive to a segment of the electromagnetic spectrum with wavelengths between 380 and 770 nm. The spectral distribution of light is perceived physiologically as color, with the small wavelengths appearing violet-blue and the longer wavelengths deep red. The sensitivity of the eye is not uniform over this visible region. Through experiment it has been shown that the eye's sensitivity peaks at 555 nm and falls of rapidly as each end of the visible band is approached (see figure V.l). It should be noted that the spectral efficiency of the eye given in the graph is an average. In general, the efficiency of an eye varies quite widely from person to person.

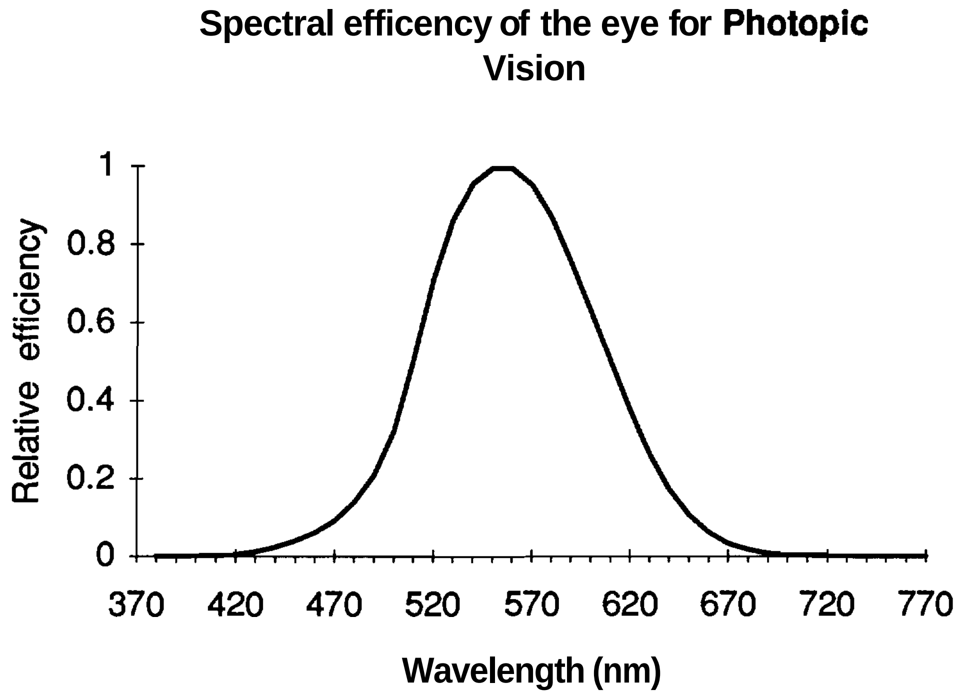

Figure (V.l)

Except in controlled laboratory conditions, the light reaching the eye is not monochromatic, but instead contains a distribution of power over a range of wavelengths. Light which appears 'white' actually consists of an equal amount of power at each wavelength of the visible band. If the spectral power distribution contains more power in the red portion of the spectrum, the light has a red tint and is called warm white. Conversely, if the spectral distribution is peaked in the blue region of the spectrum, the physiological sensation is a white light with a bluish tint usually described as cool.

The unit of luminous intensity is known as the Candela. Originally, one candela was the luminous intensity of a spermaceti candle burning at a specified rate. Obviously, this is hardly a reproducible standard and it is not used today.

It is a well known fact that as an object's temperature is increased, it begins to produce visible light. This effect, known as incandescence, was accurately explained through quantum mechanics by Max Planck in 1901. Planck's equation shown below relates the spectral power density of light emitted from a perfect radiator to the object's temperature.

$$M_\lambda = \frac{2\pi hc^2\lambda^{-5}}{e^{hc/\lambda kT} - 1}$$

This relation can be used to describe the spectral distribution of an incandescent light source by specifying the temperature of the radiating object. Since temperature can be measured quite accurately, Planck's equation can be used to define an illumination standard to which other sources may be calibrated. The Waidner and Burgess blackbody standard has been designed in this fashion using the melting point of platinum (2042 K) as the standard. To make this new standard agree with the old candle based standard the resulting luminance is assigned a value of 60 candelas per square centimeter.

While the candela describes the intensity of a light source, the lumen quantifies luminous flux. A one candela (cd) point source emits a total light flux of 4π lumens (lm). What should be understood is the unit of luminous intensity is defined based on what the eye sees and not on a radiometric measurement in watts.

In order to evaluate the efficiency of lighting systems a relation between light output in lumens and radiant power in watts is needed. This can be done as follows: If the Waidner and Burgess blackbody standard is modeled as a perfectly diffusing blackbody source and its output at each wavelength is multiplied by the corresponding efficiency of the eye at that wavelength, the resulting number is proportional to the luminous exitance of the source. For example, if the 60 lm/cm^2 from the blackbody standard is used as a reference point, it can be shown that each watt of light output at 555nm is equivalent to 683 lumens. This conversion factor allows us to calculate the amount of luminous flux produced from any spectral distribution M_λ since the efficiency of the eye with wavelength, $V(\lambda)$ is known.

$$\Phi = 683 \int_{380nm}^{770nm} M_\lambda V(\lambda) d\lambda$$

The quantity Φ/Watts is known as the efficacy of a light source. It measures a lamp's efficiency in converting electrical power to useful light.

V.3 Lamp Designs

With the concept of efficacy defined, it is possible to compare the relative efficiencies of the various lamp designs. Often just as economically important as high efficiency is lamp lifetime and, of course, cost. To make useful comparisons between the different lamps, one must consider all the pros and cons of each design and judge the overall suitability of the lamp for a given application.

V.3.1 Incandescent Lamp

The light produced by an incandescent lamp is due to blackbody radiation of a tungsten filament at a temperature between 2500 and 3000 K. At these temperatures, Planck's radiation law shows that most of the electromagnetic radiation produced by these lamps is in the infrared region where our eyes are not sensitive. As the temperature of the filament is increased, the spectral distribution shifts further into the visible range and thus increases the efficacy of the lamp. Since tungsten melts at 3650 K there is obviously a tradeoff between efficiency and lamp life. Lamps operated at 2500K usually have a maximum efficacy of 10 lm/W and a lifetime measured in the 2000 hour range, while lamps operated near 3000K have an efficacy of 21 lm/W and a lifetime of less than 1000 hours.

To prevent arcing around the filament, a fill gas of 85% argon and 15% nitrogen is usually introduced into the bulb. A disadvantage of this fill gas is that it conducts heat away from the filament, thus requiring more electrical power to reach the desired temperature. Since the heat transfer depends on the surface area of the filament, large thick filaments in high wattage lamps tend to have less surface area per watt then the thin filaments of small wattage lamps. Therefore, installations using fewer high wattage lamps will be more efficient that one using many small wattage lamps. For example, a certain 200-W GE lamp has an initial efficacy of 18.5 lm/W while a 75-W GE lamp has an efficacy of 15.9 lm/W. Both lamps operate at nearly the same filament temperature, so the difference in efficacy can be traced to a larger flow of heat (per watt) from the filament in the smaller lamp.

Another type of incandescent lamp is the tungsten-halogen. This lamp differs from the standard incandescent as it contains a halogen gas, usually bromine or iodine. When a halogen is introduced into the bulb a regenerative cycle is set up which causes the tungsten that has boiled off the filament to form a tungsten-halogen compound. This compound flows by convection currents back to the filament where the intense heat causes the tungsten compound to disassociate and the tungsten metal is returned to the filament. This cycle prevents the tungsten from condensing onto the bulb envelope and darkening the bulb. A tungsten-halogen lamp's operating range is between 3000-3400K with an efficacy from 19 to 22 lm/W. In addition to the higher efficacy, the elimination of the bulb blackening problem allow a halogen lamp to maintain its desired light output over the life of the lamp.

V.3.2 Fluorescent lamp

The most common type of lighting system in indoor use today is the fluorescent. The fluorescent lamp gets its name from the fluorescence effect of the phosphors that line the inside of the lamp tube. A typical fluorescent lamp consists of a long glass cylinder filled with a mixture of mercury vapor and argon. In operation, an electric current is passed through the gas mixture causing excitation of the mercury atoms. The ionized mercury vapor emits photons at several wavelengths with the most dominant emission at 253.7 nm. This 253.7 nm light strikes the phosphors causing them to fluoresce and emit light in the visible region of the spectrum. Some of the early fluorescent lamps had very poor color rendition but this has been corrected by improvements in phosphor technology. Some of the new tri-color phosphors have made the spectral balance of fluorescent lamps very acceptable. With the proper choice of phosphors, the spectral distribution of the light can be controlled from a bluish or "cool" cast to a warm reddish light.

Unlike an incandescent lamp, the fluorescent needs support circuitry to start and maintain the discharge. This device, known as the ballast, has gone through many design variations over the years but its main purpose has been the same. It must present a large potential across the tube to ionize the gas, and once started it must regulate the current through the tube against line voltage changes and variations in lamp voltage. A rapid-start ballast is illustrated in Figure V.2.

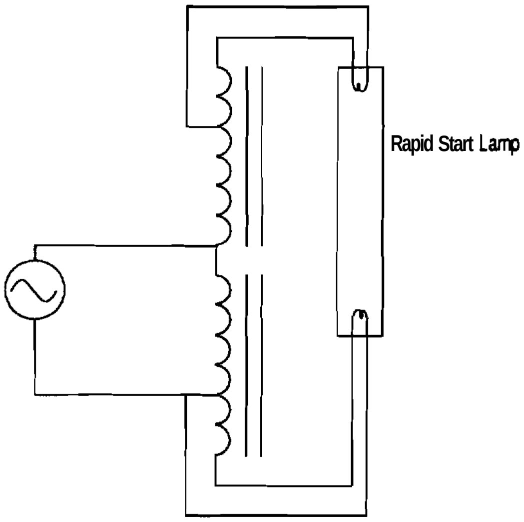

Figure V.2

Research has shown that the conversion efficiency from electrical power to the 253.7 nm UV line can be improved if a high-frequency ac supply is used to create the discharge. This is what is done in the electronic ballast. These new electronic ballasts have become more commonplace as the price of the high voltage semiconductors used in the inverter have fallen. A block diagram for a typical electronic ballast is illustrated in Figure V.3. The electronic ballast operates on the principle of rectifying and filtering the incoming 60Hz AC to produce DC, and then pulse-width modulating the DC at a high frequency, typically between 20-25 KHz. This high frequency AC is applied across the lamp's electrodes and excites the vapor.

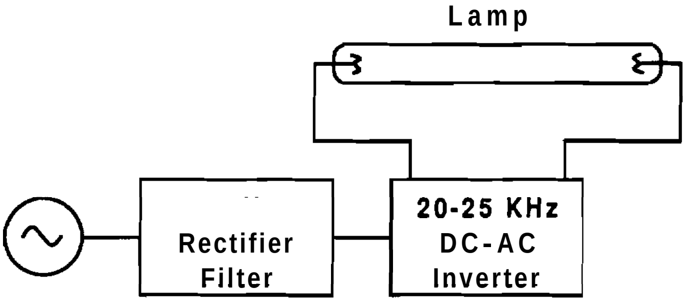

Figure V.3

Because the electronic ballast performs its ballasting operation in an efficient switched mode, it is far more efficient than the standard 60Hz magnetic ballasts. In addition, studies have shown that exciting the mercury vapor using high frequency AC produces an increased efficacy for a given lamp than would be produced at 60Hz. The combined effect of reduced ballast losses and increased lamp efficacy improves to total system efficacy by up to 20%.

Another energy saving feature of some electronic ballasts is a lamp dimming capability. Because the lamp current is regulated electronically, a dimming feature can be designed much easier and more efficiently than would be possible in a standard magnetic system. Usually the lamps efficacy is reduced at these low levels, but energy savings can be realized by using reduced levels of light whenever possible.

Unfortunately, electronic ballasts are not without their problems. The main complaint is the generation of harmonic currents in the rectifier and filter stage. Standard magnetic ballasts produce harmonics too, but these usually only contain significant energy in the third and fifth harmonic. The electronic ballasts tend to produce similar amounts of third and fifth but also contain higher order harmonics.

Much of the research on fluorescent lamps is involved with developing phosphors that convert the ultraviolet radiation at 253.7 nm to visible light with high efficiency. Some of these new phosphors in conjunction with the electronic ballasts are yielding system efficacies of more than 80 lm/W. This is quite a significant improvement over the standard incandescent's efficacy of 18 lm/W.

V3.3 High intensity discharge lamps

The term high intensity discharge lamp describes a class of lamps whose light is produced directly from the photons emitted from a gas which is excited by an electric discharge. These lamps emit light at discrete wavelengths and generally have poor color rendering qualities although lamps such as the metal-halide are getting better in this regard. While similar to the fluorescent in principle of operation, the arc tube is much smaller, usually on the order of a few inches, and the pressures present in the gas are much higher. Since the arc is confined to a small region in space, it comes closer to approximating a point source. This makes the design of reflectors that concentrate the light into relatively narrow beams possible, allowing the designer to selectively illuminate a region and minimize the amount of wasted light.

There are three main types of HID lamps in use today; the mercury vapor, metal-halide, and high-pressure sodium. All three are of a similar design, with the main differences being the size and material used in the arc tube, and of course, the element which is excited to produce the light.

In the mercury vapor lamp, the high operating temperature of the arc tube causes a much higher vapor pressure than a standard fluorescent. This increases the probability that mercury atoms are excited to higher energy states through multiple collisions with electrons. The main spectral lines in the mercury discharge occur at 253.7, 404.7, 546.1, 577, and 579 nm. Some lamps contain a phosphor coating to reclaim some of the 253.7 nm UV energy which would normally be absorbed by the outer glass envelope of the lamp. Since the spectral distribution of the light produced by this lamp is heavy in the blues and greens, the resulting light yields poor rendition of colors. In addition to the poor color quality, the lamp's efficacy of 45 lm/W is much below that attainable with the metal halide lamp. The only real advantage to the mercury vapor lamp is its long life, averaging 24000 hours. For these reasons, the mercury vapor lamp is not the best choice for new designs, unless extreme long life is desired.

The metal halide lamp solves many of the problems associated with the mercury vapor, the most significant being the spectral distribution. In a metal halide lamp, a combination of metal iodide salts is used to produce a balanced output over the entire visible range. The most common metal halide uses sodium and scandium iodide which gives a white light with just a slight bluish cast. The efficacy of this lamp averages 85 lm/W, exceeded only by the sodium vapor lamp. Its high efficiency and white light has made the metal halide the first choice for applications such as factory and stadium lighting.

Both the metal halide and mercury vapor lamps use a very similar ballast. The typical design consists of an autotransformer, built with an intentionally high value of leakage reactance to regulate the lamp power against changes in lamp and line voltages. Ballast losses are significant, averaging 10% of the lamp's rated power. However, efficient electronic ballasting technology is not as cost effective for HID lamps as it is for fluorescents as the design difficulties involved make the unit prohibitively expensive. This may change as high power semiconductors and magnetic materials become less expensive.

With an average efficacy of 95 lm/W and a maximum of 140 lm/W for some very high wattage lamps, the high pressure sodium is the most efficient lamp in common use. This lamp is more expensive than either the mercury vapor or metal halide due to the specialized construction of the arc tube. Sodium vapor is very reactive and a practical lamp was not realizable until 1965 when polycrystalline alumina was developed and used in the arc tube. A large reason for the sodium vapor lamp's high efficacy is its peak spectral output in the 580 nm region where the eye is very sensitive. Unfortunately, this peak causes the light to have a yellow-orange tint which makes for very poor color rendition. This lamp is therefore quite suitable for lighting outdoor areas such as parking lots where high illumination levels is more important than accurate color rendition. The ballast used for the sodium vapor lamp is much more expensive than those used on the other discharge lamps. The small size of the arc tube makes the incorporation of a starting electrode impractical, thus this lamp needs a separate source of high voltage to strike the arc. Usually, a separate high-voltage trigger circuit is added to the standard magnetic ballast circuit.

V.4 Luminaires

Regardless of what type of lamp is desired for a particular application, it must be installed in some type of fixture which holds the lamp and directs the light where it is needed. This device is known as a luminaire. Ideally, all the lumens produced by the lamp would be directed toward and reach the workspace. Obviously, this is does not happen since some of the light is sure to be trapped in the luminaire and wasted. Manufacturers often give a rating of efficiency called the coefficient of utilization or CU. Since the CU is the ratio of the light that reaches the workplane to the light output of the lamp, it is a useful index to describe the overall efficiency of the system. In general, the coefficient of utilization is not given as a single number, but instead as a table which includes factors such as fixture mounting height, room size and wall reflectance.

If lighting design can be integrated into the architectural design of a room, a very efficient system can usually be designed. In the 1960s it was common to light a room with completely indirect lighting. The usual scheme was to use many high wattage incandescent lamps in bowl shaped reflectors that reflected 100% of the lamp's light toward the ceiling. The reflected light from was then used to illuminate the workspace. Although this type of system was terribly inefficient. It did provide a very uniform source of light without shadows. At the other extreme, a lighting system can be designed that concentrates light exactly where it is needed. This method has its advantages in that a minimum amount of power can be used for a given application. The disadvantage is workers can easily get in the path of the light and produce unwanted shadows.

Frequently it is desirable to improve the efficiency of the lighting system in an existing room. Often this can be done with minimal cost by upgrading the reflectors in fluorescent lighting fixtures. Some reflector inserts have been designed that take the place of one or more fluorescent lamps. In this way, fewer lamps can be used to provide the nearly the same illumination levels in the room. In some instances, such as a factory which is illuminated by many inefficient incandescent lamps, choosing one of the more efficient **HID** lamps and a suitable luminaire will significantly reduce energy costs and often pay for the upgrade in a short time.

V.5 New lamp designs

The lighting program at Lawrence Berkeley Laboratory has been key in developing new lighting technologies. Among the most interesting developments is the electrodeless fluorescent lamp. The basic physics behind the operation of this lamp is almost identical to the standard fluorescent with the difference arising in the method used to excite the mercury vapor. In an electrodeless lamp, a high frequency oscillator/amplifier produces RF energy with significant field strength to excite the vapor. Since this RF energy can pass through glass, no metal electrodes are needed inside the lamp envelope. Eliminating the electrodes has many benefits. First, electrode failure is the main failure mode in a standard fluorescent. Without electrodes, the life of the lamp depends only upon the lifetime of the phosphors, which can be in excess of 20000 hours.

One prototype of this lamp, soon to be released in the consumer market, uses a 13.56 **MHz** RF source to provide the excitation. **It** produces light equivalent to a 100 watt incandescent lamp while using only 25 watts AC power. A sketch of this lamp is shown in figure **V.5**.

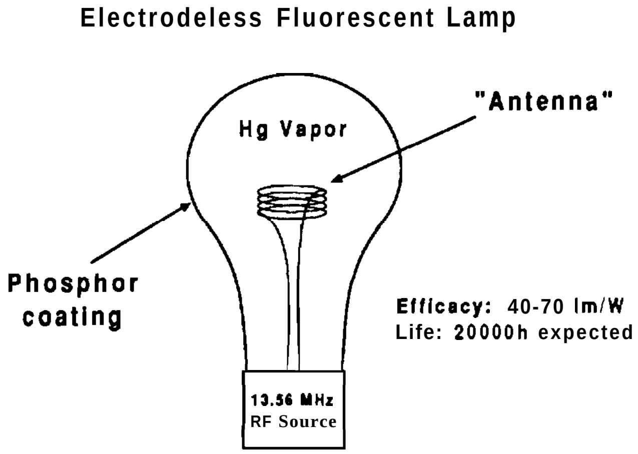

Figure V.5

The lamp and ballast are self contained and the unit is supplied with the standard Edison base, suitable for installation anywhere a normal 100W lamp would be used. Since this lamp uses significant amounts of RF energy, providing adequate shielding is quite difficult. The difficulty in shielding these RF excited lamps is one of the main reasons they are not in common use. With an design efficacy between 40 and 70 lm/W the new lamp is slightly less efficient than a standard fluorescent, but gains the advantage of small size and the ability to replace standard incandescents.

V.6 Conclusions

From the study of the various types of lamps, it is apparent that the most efficient lamp is not the best choice for all applications. Factors such as color quality, initial cost, and lamp life must all be considered together. Table **V.6** summarizes the efficacies, color quality, and lamp life of the various lighting systems discussed.

Lamp	Efficacy (avg.) lm/W	Color Quality	Life (hours) (avg.)
Incandescent	18	Very good	1000
Fluorescent	70-80	Dependent on lamp phosphors, some quite good	12000
Mercury Vapor	45	Very poor, rich in blues and green.	24000
Metal Halide	85	good -- slightly cool	10000
High Pressure Sodium	95	poor -- rich in yellows/orange	20000

Table **V.6**

It should be also noted that the design of an efficient lighting system should not come as an afterthought to the architectural design of a room. If the purpose of the room is known from the beginning, the proper choice of luminaire can significantly reduce the amount of power consumed for a desired amount of useful light. On the other hand, if the task is upgrading an existing lighting system, a few of questions should be asked are: Do the energy savings of the new lighting system merit the expense of the upgrade? Where is the light needed? Is the color quality of the new lamps going to be objectionable? Answers to these questions should be used as guide to determine the optimal course of action.

V.7 References

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[2] Norbert Lechner, "Heating, Cooling, Lighting Design Methods for Architects," Wiley, New York, 1991

[3] Albert Thumann, "Lighting Efficiency Applications," The Fairmont Press Inc., Liburn GA., 1992

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Chapter VI Energy-Efficient Motors

Steve Pekarek

VI.1 Introduction

It is a well-known fact motors represent the largest load to most utility systems, using over two thirds of the total electric energy consumed in this country [1]. In fact, energy consumed by electric motors represents a cost of over 90 billion dollars a year. Since the mid 1970's, when the nation was threatened by an energy crisis, a great deal of work has gone into minimizing the power consumed by motors. This work led to the introduction of more efficient motors, or motors that had lower losses than their predecessors. In the late 1970's manufacturers started defining their newly designed motors as energy-efficient or high efficiency motors. In order to standardize this term, NEMA set requirements on what could be considered an energy-efficient motor as opposed to a standard efficiency motor. This definition is basically a series of tables which give the necessary nominal/minimum efficiency rating a motor must meet to be considered energy-efficient. A representative table will be shown in the next section.

Although the energy-efficient motor has been on the market for over a decade, only 11% of the motors sold today are energy-efficient. Most plant engineers purchasing new equipment rarely consider the motor's efficiency. Many haven't heard the term, and some are even skeptical about the economic advantage of the energy-efficient motor. This paper will analyze the design, losses, economic advantage, and future of the energy-efficient motor. Because induction motors make up the largest portion of today's market, the emphasis of this paper will be placed on energy-efficient three phase induction motors.

Before one can analyze the energy-efficient motor several terms must be defined. First of all, the term efficiency is defined as:

$$n = \text{Efficiency} = \frac{\text{Power Out}}{\text{Power In}} \qquad \text{Eq. VI.1}$$

or written another way:

$$n = \text{Efficiency} = \frac{\text{Power Out}}{\text{Power Out} + \text{Losses}} \qquad \text{Eq. VI.2}$$

Secondly, motors are labeled with NEMA nominal and minimum efficiency ratings. The term nominal efficiency is simply the mean value of efficiency for a population of motors with the same design. The minimum efficiency is the lowest value of efficiency one can expect of a particular motor. Thus, if a motor was purchased, one would expect it to have an efficiency close to its labeled nominal efficiency and not lower than its labeled minimum efficiency.

VI.2 What is an Energy-Efficient Motor?

Until recently there was no standard definition for an energy-efficient motor. Standard motors were designed with efficiencies high enough to meet the allowable temperature rise for the rating. In 1974, with the increase of energy costs, one motor manufacturer worked on the development of a line of motors that would decrease motor losses by 25%. Soon after, the industry as a whole made an effort to decrease the watt losses of induction motors. In 1990 NEMA adopted a standard for future design of energy-efficient motors which is contained in reference [2]. As mentioned above this standard consists of a set of tables that give nominal and minimum efficiency ratings a motor must have to be labeled energy-efficient. A typical example is shown below in Table VI.1, which shows full load nominal and minimum efficiencies for a two-pole TEFC energy-efficient induction motor. Figure VI.1 compares efficiencies of standard, first generation , and current energy-efficient induction motors [2]. The change in first generation and current energy-efficient motors is due mostly to better manufacturing and a higher quality of laminated steel which minimizes stator core losses.

hp	Nominal	Minimum
1.5	82.5	81.5
2.0	84	82.5
3.0	84	82.5
5.0	85.5	84.0
7.5	87.5	86.5
10	88.5	87.5
15	89.5	88.5
20	90.2	89.5
25	91	90.2
30	91	90.2
40	91.7	91.0
50	92.4	91.7
60	93	92.4
75	93	92.4
100	93	92.4
150	93.6	93
200	94.5	94.1

Table VI.1 - NEMA Full Load Nominal and Minimum Efficiencies for Two-Pole Energy-Efficient Induction Motors.

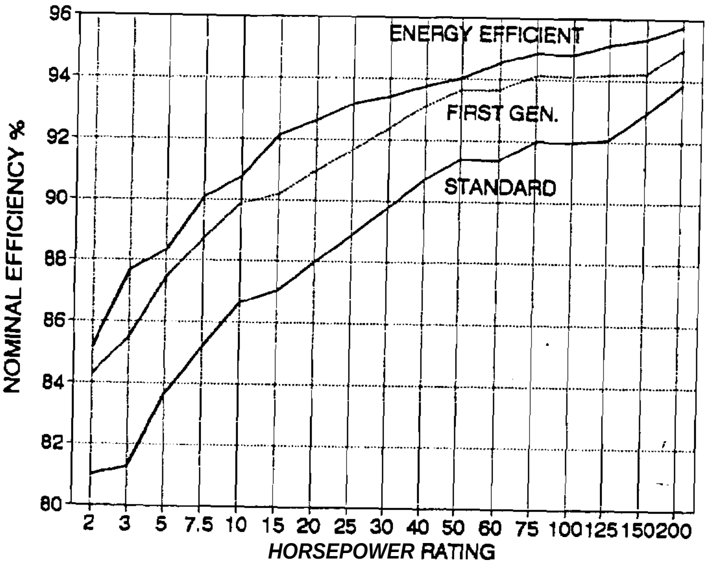


Figure V1.1 - Comparison of standard, first generation, and current energy-efficient TEFC induction motor efficiencies [2].

VI.3 Energy-Efficient Motor Losses

In this section, the losses associated with energy-efficient induction motors will be analyzed. The design changes that are used to convert a standard motor to an energy-efficient motor will also be seen.

From Equation VI.2 it is obvious that in order to increase a motor's efficiency the losses must be reduced. **An** induction motor will generally have five types of losses associated with it. These are given in Table VI.2 along with a general indication of the average loss distribution [2]. This distribution is by no means an exact representation of loss percentage, for each motor will have a different loss distribution depending on its age, materials, operating conditions, etc..

Motor Component Loss	Total Loss, %
Stator power loss I^2R	37
Magnetic core loss	20
Rotor power loss $I_R{}^2R$	18
Friction and windage	9
Stray load loss	16

Table VI.2 - Typical loss distribution of an induction motor [2].

The primary I^2R loss is the ohmic loss due to current passing through the stator winding. Typically, motor designers will reduce this loss by increasing the cross-sectional area of copper and using higher quality conductors in order to reduce the stator winding resistance. This method is used in nearly all energy-efficient motor designs.

The magnetic core loss occurs in the stator laminated steel core due to the combined effect of hysterisis and eddy current losses. Magnetic core losses are controlled by reducing the flux density in the stator core. This can be achieved by increasing the length of the stator core or using a higher grade of laminated steel. This technique is usually used as well to reduce the magnetic core losses in energy-efficient motors.

The rotor I^2R loss is generally expressed as the ***slip loss*** and is given in Equation VI.3.

$$\text{Rotor Loss} = \frac{(\text{output hp}*746 + FW)S}{1 - S} \qquad \text{Eq. VI.3}$$

where S equals the slip and FW equals the friction and windage loss. The rotor loss is reduced by increasing the amount of material in the rotor or increasing the total flux across the air gap into the rotor. The extent of these changes is limited by the minimum starting torque, maximum locked rotor current, and also the minimum power factor required. Thus often the rotor losses of the energy-efficient and standard efficient induction motor will be almost equivalent.

The friction and windage losses are associated with the rotation of the motor. These are due to the friction in the bearings and the windage loss of the ventilation fan and other rotating elements. In fan cooled motors the major contributor to the windage losses is the fan. Since energy-efficient motors have less heat dissipated because of better material, the fans used to cool the motor can be smaller than those cooling standard motors. These smaller fans lead to smaller windage losses in energy-efficient TEFC motors. However, the extent of the loss savings does not usually have a large impact on the increase in efficiency.

Stray load loss is the difference between the total loss and the sum of the other four losses. It is caused by several different factors and is the most elusive of the five losses. The cure for stray load loss is very technical and cannot be easily explained without a thorough understanding of motor design. Basic control of the loss is accomplished by a combination of good design and careful manufacturing of the motor. It is crucial to control the stray load loss in order to create an energy-efficient motor.

Table VI. 3 shows a comparison of the losses between a standard and energy-efficient versions of a 50hp induction motor [3] . One can see that the highest loss reduction came in the stator, magnetic core, and stray load losses.

Although the specific numbers from Table VI.3 vary from motor to motor, these three areas are usually responsible for over 90% of the total loss reduction in converting from standard to energy-efficient motors.

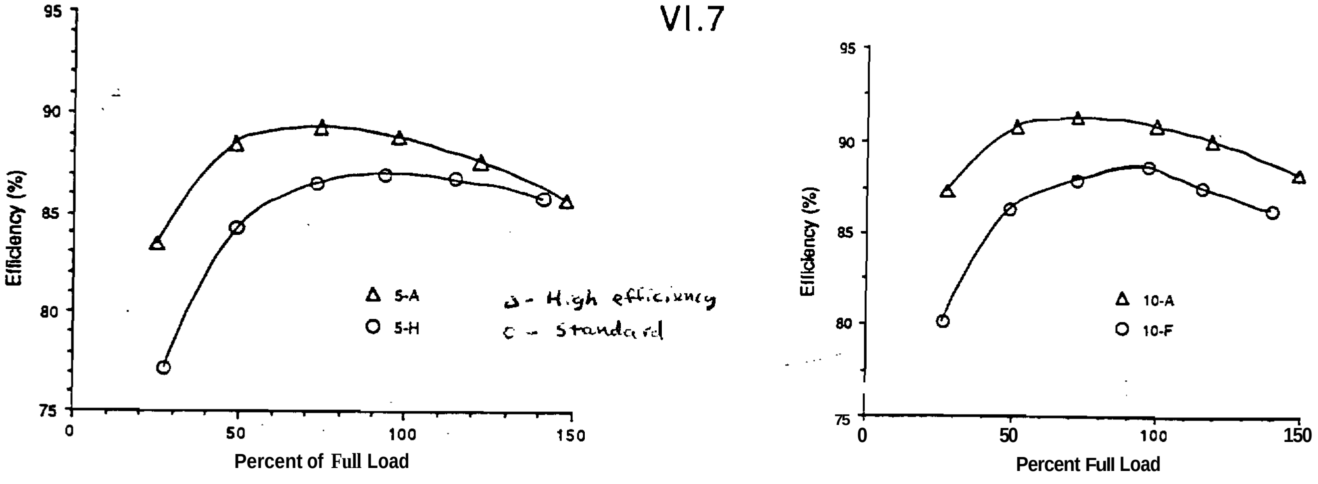
	Standard Motor Losses - kW	Energy Eff. Motor Losses - kW	kW Loss Improvement
Stator I^2R	1.319	.911	.408
Magnetic Core	.725	180	.545
Rotor I^2R	.646	.668	.022
Friction & Wind	.373	.281	.092
Stray Load	.852	.299	.553
Total	3.915	2.339	1.576

Table VI.3 - Comparison of losses between a standard and energy-efficient 50hp induction motor [3].

VI.4 Energy-Efficient Motor Performance

Recently the North Carolina Alternative Energy Corporation sponsored a test program to form a basis for recommending energy-efficient motors to industry in North Carolina. This test compared the efficiency of standard and energy-efficient motors and also did comparisons on new versus rewound motors. One interesting test that was performed compared the efficiencies of both 5 and 10 hp motors over a wide range of loads. The results of these tests are shown in Figure VI.2 [5].

From these results one can observe that energy-efficient motors attained their maximum efficiency near 75% of their rated load, while standard motors attained their maximum efficiency closer to their rated loads. It is also seen that energy-efficient motors operate near their peak efficiency over a wider range of loads than the standard motors, thus the difference in efficiencies is even greater at less than full load, where most motors operate.



(a)

(b)

Figure VI.2 Comparison of efficiencies between standard and energy-efficient 5 hp (a) and 10 hp (b) induction motors under various loads [5].

The energy-efficient motor has also been found to handle nonsinusoidal voltage better than their standard counterparts [4]. Many times standard motors must be derated by 10-15% when supplied by an adjustable speed drive that produces substantial harmonics. Energy efficient motors, on the other hand, rarely need to be derated because of their higher thermal margins and lower losses. Thus, the energy-efficient motor can prove to be better suited to asynchronous drive applications than standard motors. Figure VI.4 shows a comparison between a 100hp, 1800rpm standard induction motor and a 100hp, 1800rpm energy-efficient induction motor, both with non-sinusoidal supply voltages [2].

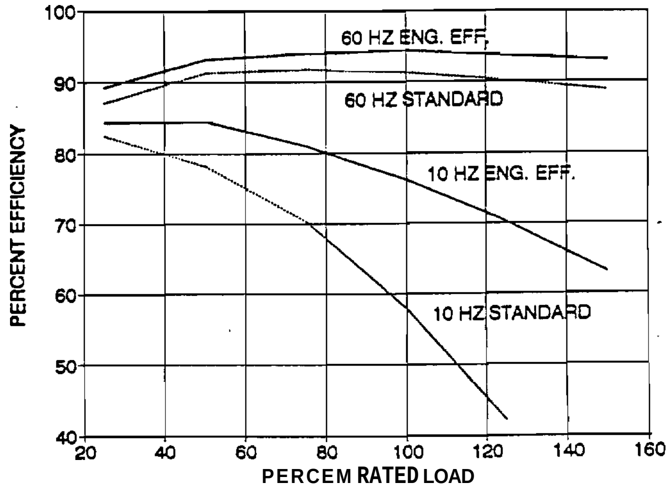


Figure VI.3 Comparison of 100hp, 1800rpm standard and energy-efficient induction motor efficiencies with non-sinusoidal supplies [2].

VI.5 Economic considerations

With all the apparent advantages of an energy-efficient motor, one may ask why they continue to represent only a small portion of the motor market. A significant disadvantage is their cost; energy-efficient motors are made with better materials, more sophisticated manufacturing, and better designs, all of which add to the cost of the product.

It is easy to calculate the savings associated with an energy-efficient motor. The annual cost savings for two motors of different efficiencies operating at the same load can be calculated using Equation VI.4.

$$S = .746 * hp * P * H\left(\frac{100}{\eta 1} - \frac{100}{\eta 2}\right) \qquad \text{Eq. VI.4}$$

where

S = annual saving, \$/yr
hp = horsepower output
P = power costs, \$/kWh
H = running time, hr/yr
$\eta 1, \eta 2$ = Efficiencies of compared motors

The years needed to pay back the initial difference in cost between the two motors can be calculated from

$$P = \frac{\text{difference in cost}}{S} \qquad \text{Eq. VI.5}$$

where P is the number of years needed to make up the difference in initial cost. Note that the time value of money was not taken into account in either of these equations.

For a calculation involving the time value of money both [2] and [3] provide all the necessary equations.

Using these equations and average nominal values of the standard and energy-efficient induction motors on the market today, one can calculate the annual savings and the payback period of an energy-efficient motor investment. This is done in Table VI.4 based on a 4000-hr/yr operation a $.06/kWh power cost, and trade prices for the motors [2].

hp	Nom Eff Standard Motors	Nom. Eff energy-efficient motor	Annual Saving kWh	Annual Savings, $	Months to Payback
1	73	83.5	514	31	6
2	77	84.3	671	40	8
3	80	87	900	54	11
5	82	87.9	1221	73	12
7.5	84	90	1776	107	10
10	85	90.6	2170	130	11
15	86	91.6	3182	191	11
20	87.5	92.1	3407	204	13
25	88	92.6	4211	253	14
30	88.5	93.1	4998	300	13
40	89.5	93.9	6249	375	10
50	90	94.1	7223	433	12
60	90.5	94.4	8173	490	10
75	91	94.8	9858	591	12
100	91.5	95.1	12345	741	8
125	92	95.1	13216	793	11
150	92.5	95.3	14217	853	7
200	93	95.5	16799	1008	13

Table VI.4 - Calculation of annual savings and payback period for standard versus energy-efficient motors with 4000 hr/yr operation, a $.06/kWh power cost, and trade prices for the motors [2].

One can see that for this case the typical payback period is close to a year. If the same costs were used, but the hours of operation was increased to 6000 hr/yr the savings would be even greater. It is easy to see that if the motor is on a fifteen year life cycle, choice of the energy-efficient motor would yield significant savings.. Applications in which the energy-efficient motor would be most cost effective include pumps, fans, and equipment running in a continuous process. In applications such as valve operators, door openers, etc., energy-efficient motors are usually not cost effective because of the long payback period associated with intermittent duty operation.

VI.6 Advantages and Disadvantages of Energy-Efficient Motors

The most obvious advantage of energy-efficient motors is energy savings; however, there are other advantages. One advantage is the decrease in operating temperature associated with energy-efficient motors. Because they have 20-40% less loss, they run cooler, which helps increase bearing life, lubricant life, and insulation life. Energy efficient motors also suffer less thermal stress than standard motors when operating at small overload conditions. All of these things significantly add to the life of the motor. The advantages listed above are also significant, particularly the superior performance of energy-efficient motors in nonsinusoidal and variable load applications. It has also been found that the efficiency and power factor of energy-efficient motors are not as sensitive to voltage variations as standard motors [2].

There are some disadvantages to energy-efficient motors. First, the additional cost of these motors over standard motors may not be prove to be cost effective for many applications. Second, because energy-efficient motors have lower losses, their slip is smaller and thus their speed is slightly higher than that of a standard motor. Thus when an energy-efficient motor is driving a load whose power increases with the cube of the speed (some pumps), the increased speed of energy-efficient motor may cut their savings significantly. Their small slip also causes them to have lower torque than a standard motor.

Another potential problem exists from the fact that the power factor of a motor is inversely proportional to its efficiency as can be seen in Equation VI.5. Thus, in order to maintain the same power factor for an energy-efficient motor and standard motor, the stator current must be reduced. This can proved to be difficult to do depending on the motor, and thus some energy-efficient motors will have a lower power factor than standard motors.

$$PF = \frac{\text{output hp} * 746}{\text{voltage} * \sqrt{3}\ \text{efficiency} * I} \qquad \text{Eq. VI.6}$$

VI.7 Future of Energy-Efficient Motors

Although energy-efficient motors have been in existence for more than a decade, they still have not found a large share of the market. This is mainly due to higher costs, lack of knowledge, and skepticism. In order to combat these problems, incentive programs, such as rebates, tax credits, and performance contracts have been introduced to urge industry to invest in the energy-efficient motor. Software has been written to calculate the energy savings, demand savings, return on investment, and simple payback of energy-efficient versus standard motors.

There is also a great deal of research being conducted to produce a new generation of energy-efficient motors. Presently, high efficiency motors are created by making incremental changes in standard designs such as using larger conductors or better quality iron. However, more advanced motors are being designed in which more fundamental changes in the motor design are being taken to make significant efficiency boosts.

One such machine is the permanent magnet synchronous machine being developed by McCleer Power and the University of Tennessee [6].

In this machine, permanent magnets are mounted on the rotor and are pulled along by a rotating magnetic field created by the stator coils. Variable speed is achieved by varying the voltage and frequency of the stator using a five phase electronic power converter. **An** important feature of this motor is that its design has been optimized for use with a particular power converter, while most motors are designed to operate with a sinusoidal source. Preliminary studies of this machine have been made and its efficiencies are compared with both the energy-efficient and standard induction motors in Figure **VI.4** [1].

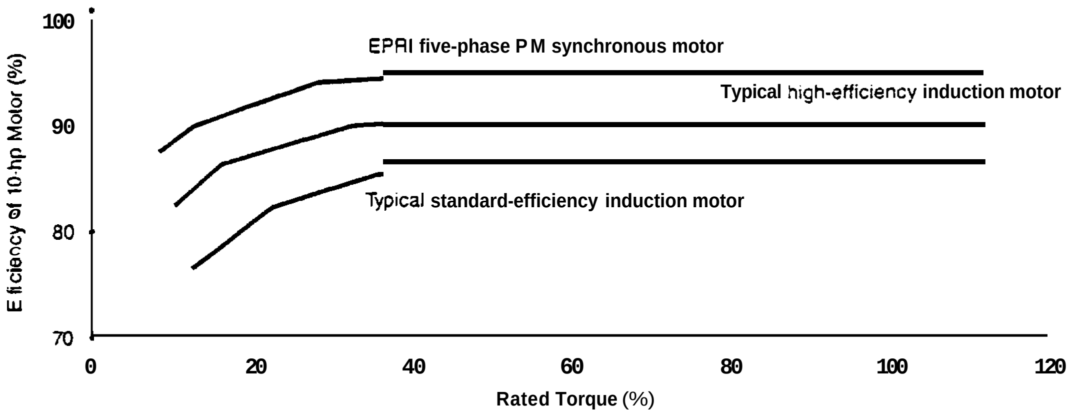


Figure **VI.4** Comparison of the five phase PM synchronous motor with typical energy-efficient and stand induction motors [1].

New energy-efficient designs for other types of motors such as the reluctance, brushless DC, and fractional horsepower permanent magnet are also expected soon. With all the new designs, incentives, and software available, the energy-efficient motor may be the choice of the future.

VI.8 Conclusions

In summary, this paper provides a brief insight into energy-efficient motors. Their design, losses, savings, advantages, and disadvantages were reviewed and compared with those of standard motors. It is easy to see energy-efficient motors do have a valuable place in long-hour, continuous process applications. It is also evident that the energy-efficient motor can have a significant impact on loss reduction. In fact, it is estimated that at least 10 billion dollars a year could be saved if standard motors were replaced with their energy-efficient counterpart. Hopefully the ignorance and skepticism concerning their existence and benefits will be reduced, along with the power consumed by the nation's motors.

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VII. LOSSES IN POWER ELECTRONIC CONTROLLED LOADS

VII.I Intoduction

Power electronic converters have come to play a major role in energy conversion processes today. Primarily, compared to other methods of conversion, especially mechanical methods, power electronic converters are very efficient in power conversion, with efficiencies in the order of 95 percent. This might lead one to wonder why the subject of losses is being discussed in this context. Nevertheless, though efficient at the outset, power electronic converters introduce a whole host of problems which are quite relevant to discuss. Though the direct energy conversion losses may be quite low, the indirect losses accrued due to the use of such converters are noticeable, if not glaringly so. This chapter will discuss the various effects of power electronic converters and also dwell upon the effects on loads that utilize such converters. The impact of such converters on a power system will also be discussed. A brief overview will be presented on the methods to avoid such problems. The other aspect of this chapter will be the problem of Electromagnetic Interference (EMI) caused by power converters, which will be discussed in some detail.

VII.II Power electronic converters- an overview

Power electronic converters can be basically classified based on two criteria

- Type of application
- Type of energy conversion

The classification based on application is fairly extensive and can be outlined as shown

- Residential
- Commercial
- Industrial
- Transportation
- Utility systems
- Aerospace
- Communication systems

Typical examples can be visualized easily in each case. Electronic ballasts for flourescent lighting and induction cooking are typical applications in the residential sector. Uninterrupted power supplies and flourescent lighting have applications in the commercial sector. Power electronic converters also find enormous applications in the industrial sector where they are used for speed control of motors, induction heating furnaces and electric welding, to name a few. Transportation systems employ converters for speed control of electric motors for traction or other purposes. HVDC (High Voltage DC Transmission) is one of the areas in utility systems where power electronic converters find usage. Similar examples can be outlined for other applications. Thus, at an outset, one can appreciate the scope of application of power electronic converters and hence it does make sense to discuss their impact on the various loads and systems that utilize them.

By the type of energy conversion, power electronic converters can be classified as outlined

- AC to DC converters
- DC to AC converters

- AC to AC converters
- DC to DC converters

A fairly long list of converters lie in the above categories and [1] gives an excellent overview of the various types of converters and their methods of operation. Attention will be focussed on the problems that are associated with the use of such converters and the succeeding sections will focus on them in some detail. The following section discusses the impact of power electronic converters. Specially, by virtue of the title that has been chosen, the focus will be on the negative impact and the problems that are introduced by utilizing such converters.

VII.III Impact of power electronic converters

VII.III.I Functional aspects of a converter

Basically, a power electronic converter converts some form of electrical energy to another. As outlined earlier, the forms of energy conversion are between AC and DC in various combinations. Typically the power electronic converter consists of a combination of controllable switches which are utilised to "channelize" electrical energy in a desired form. Such switches are implemented by semiconductor devices like transistors, diodes and thyristors. For high power applications, power transistors or four layer devices like SCRs are used. A generic power electronic converter basically operates on three variables, i.e., the number of phases, the voltage magnitude and the frequency. This chapter will not dwell on the working aspects of such converters and a basic knowledge of converter operation is assumed. Since a converter is basically a network of switches, if the terminology can be used, it is clear that the losses, per se, might occur only during switching. This is the reason why such converters are highly efficient. However, it is also fairly obvious that frequent switching introduces components of other frequencies, commonly referred to as harmonics. How such components can affect loads will be discussed next.

VII.III.II Impact of harmonics and other power quality issues

Power electronic converters can cause problems that relate to power quality. Power quality, in the broad sense of the term, refers to maintenance of proper waveshape and frequency. There are many more aspects to it, but for simplicity, the above mentioned factors will suffice. How do power electronic converters contribute to power quality problems? Basically, they tend to distort the waveshape. This is fairly easy to visualize because in the case of AC to DC and DC to AC conversion, discretized switching causes the converter to generate only approximations to a sine wave instead of the actual. Over and above the fundamental frequency, higher frequency components are introduced in the form of harmonics. Again, it is illustrative to see how harmonics can cause losses to occur in the system. Apart from a fundamental component, there exist current and voltage components at higher frequencies. So, instead of power loss at the fundamental frequency, there are additional losses due to the high frequency components. This reduces the available part of energy and hence affects efficiency.

Apart from reducing the available power, harmonics also cause other problems which are not insignificant. The power factor is reduced and hence the active part of the power is reduced. So the conversion efficiency is affected. The most glaring effects can be seen in electric motors, specifically induction motors.

VII.III.III Nonsinusoidal excitation of induction motors- an example

It is commonly assumed that induction motors are supplied from a three-phase balanced, and sinusoidal set of voltages. With harmonics coming into the picture, the effects on induction motor torques are very interesting to observe and study.

Let the fundamental speed of the stator field be w,. Then at the h'th harmonic,

$$w_{sh} = hw_s \qquad [\text{VII.1}]$$

Now, corresponding to this harmonic, the slip can be written as,

$$s_h = \frac{w_{sh} \pm w_r}{w_{sh}} \qquad [VII.2]$$

It can be easily shown that this slip will generate a current harmonic given by

$$I_h = \frac{V_h}{hw(L_{ls} + L_{lr})} \qquad [VII.3]$$

where, L_{ls} and L_{lr} are ths stator and motor inductances respectively. This current harmonic can generate its own copper losses and so do other current harmonics. These additional losses are about **10** to **20** percent of the rated load. This is why power electronic converters have to be studied further to reduce the losses to a reasonable value.

In addition to causing copper losses, the harmonics cause torque pulsations which can increase the speed ripple. This is not advisable for the mechanical life of the motor. Moreoever, additional harmonics and waveshape distortion cause nonuniform heating losses which are difficult to dissipate.

Thus this is an example of how much power electronic converters can affect a system in typical and very common application. Similar problems are faced by DC drives, where, due to the high form factor excessive heating occurs in the armature which reduces the efficiency and the life of the motor. Other problems occur in synchronous motors, but basically the upshot of the entire issue is that power electronic converters introduce harmonics into the system which cause a increase in losses and a decrease in efficiency. However, these are not the only problems. There still exists the problem of EMI which will be discussed here. Still, to provide a totality to the discussion, methods will be outlined to mitigate these problems caused by power converters.

VII.III.IV Placebos- a brief look into the remedies to problems

The problems outlined above are typical of power electronic controlled loads. One might now wonder as to whether there are means for mitigating these effects and solving the problems to an extent. The problems are rather complex, because, in addition to affecting the power quality, the poor waveform of the current affects the power electronic converter itself!! So to have a look at the solutions would be in order. The problem can be attacked in two ways, depending on whether one uses a single phase input or a three phase input. In short, the solutions will be

- To improve the single phase utility interface
- To improve the three phase utility interface

The basic idea is to shape the current waveform to be as close to a sinusoidal wave as possible. In a single phase case, the input line current can be actively shaped to be sinusoidal.In the three phase case, current shaping circuits are needed for each phase. A dc-side inductor can be introduced to have uniform current flow and ensure continuity of waveshape. By current shaping one can improve waveforms and reduce losses significantly.

VII.IV The problem of electromagnetic interference (EMI)

One of the more interesting problems caused due to such converters is that of electromagnetic interference (EMI). EMI is caused by high frequency harmonics that are in the radio frequency range. Switching transients that arise in the power converters can be such that higher frequency harmonics are generated. These harmonics can be in the radio frequency range, although the energy contained in them might be small. However, due to short rise and fall times, the energy per band might be significant enough to cause interruptions in communication channels carrying information. This loss of information would be a consequence of the harmonics of the power converter. Thus this problem has been addressed well and [2] gives a very useful account of the problem.

Theoretically the harmonic components extend to infinite frequency for quasi square waveforms. Since the harmonic amplitudes are inversely proportional to their order, the RF components are of very low amplitude relative to the fundamental. Nevertheless, in their potential for causing EMI, such voltage levels may well exceed allowable limits. Other than harmonic components, the switching devices generate interference, mainly from the reverse recovery process in diodes.

VII.IV.I Reducing the EMI problem

For reducing this problem, there are some well tested techniques. The EMI is propogated in two ways

- Conducted
- Radiated

Conducted EMI can be reduced by metal cabinets around equipment which cause the signals to be grounded. For others, however, such precautions are not sufficient. Some techniques are outlined below

- Snubber circuits to reduce $\frac{di}{dt}$ and $\frac{dv}{dt}$
- Reduce the net area enclosed by a current loop
- Filters for EMI

These give some ways by which the problem can be tackled. Reducing the rate of change of voltage and currents would reduce harmonics to a large extent and also switching transients.

VII.V Conclusion

A brief overview has been presented of the problems caused by power electronic converters and some interesting applications have been presented. This study is of course a very brief survey and devoid of many details. The interested reader however, can refer to [1] and [2] for a detailed analysis. Several papers and articles have appeared on these topics and the IEEE Transactions on Power Electronics would also be a good place to study these problems further.

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