High Efficiency Lighting Using Alternative Energy Sources

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The required efficiency of a battery or solar powered lighting system usually exceeds that of a mains powered equivalent due to the limited energy available. Both lumen efficacy and power conversion efficiency must be considered in order to provide the maximum lumens per watt. This paper describes mechanisms affecting lumen efficacy.

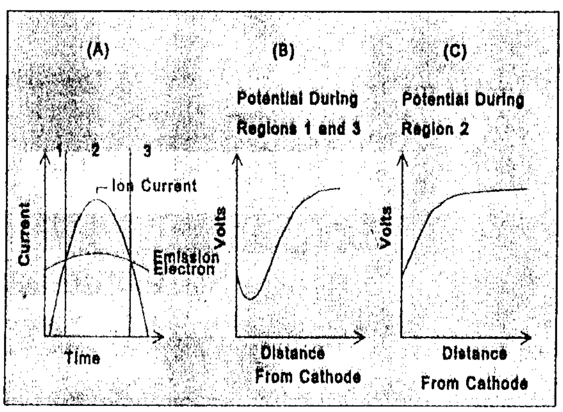
Due to the complex dynamics of electrode thermal delay and relaxation times of the plasma and electron gas, lamp performance varies considerably with supply frequency. At low frequencies, as in mains operation, the lamp periodically extinguishes and then re-ignites at every current zero. This re-ignition voltage requirement is far lower than that of a cold lamp, because the plasma remains for up to 10 ms after the lamp has extinguished and the electrodes are already at operating temperature. As the lamp re-ignites the process of cumulative ionisation follows the lamp current fluctuations resulting in a non-linear voltage-current characteristic. The periodic re-ignition reduces efficiency and the consequent waveform distortion is a source of electromagnetic interference.

As the supply frequency increases the ionisation state can no longer follow the rapid changes in lamp current and the plasma density becomes constant, resulting in a constant effective resistance throughout the cycle. A further advantage is that no periodic re-ignition is required.

Electrode fall potentials are due to a mismatch with the plasma. The cathode fall is required to assist electron emission through ion bombardment and to provide electrons with sufficient kinetic energy to enter the plasma and cause ionisation. At low frequencies the cathode electrode temperature is modulated by lamp current and so high cathode falls are required at every current reversal. The anode fall results from a restricted surface area for alighting electrons and at low frequencies the current form factor is high because of plasma density modulation. It follows that as the frequency increases the electrode falls decrease resulting in increases in efficiency.

The use of direct current has a similar effect on efficiency as high supply frequency because the plasma density remains constant.

The mechanism responsible for plasma relaxation is ambipolar diffusion. This is the process whereby electrons and ions travel to the wall of the tube where they recombine. Ambipolar diffusion (T_a) is 1 ms whilst the electron temperature relaxation time (T_e) is 5 ms. As the plasma relaxation time is less than 10 ms, at mains frequencies both the plasma density and the electron temperature are modulated by the instantaneous current variations. There are, however, frequencies where the current variations are followed by the electron temperature (T_e) but not by the whole plasma.



To illustrate this phenomenon consider a modulated dc discharge. When the modulation period is greater than both the plasma and electron temperature relaxation times, the result is a slowly varying dc discharge with hardly any variation in electron temperature. This is because only slight changes in electron temperature cause current variations due to the exponential relationship between electron temperature and the ionisation rate. When the modulation period ($2\pi/\omega$) is much less than both periods then the discharge is too slow to follow the variation, and the electron temperature adjusts to a level corresponding to the average current.

When the modulation period is in the region $T_a \le 2\pi/\omega \le T_e$ the modulated discharge current causes a modulation in electron temperature with no modulation in plasma concentration. However, as the modulation coefficient increases above 0,5 the concentration of excited atoms increases. The result is that there are relatively more electrons of high energy than there would be in a dc discharge with the same average electron energy. This causes an increase in populations of electrons at high energy levels, resulting in an increase in 436 nm emission. As this emission is visible, blueish light, no phosphor conversion is necessary and so efficiency is improved. These effects occur when a rapid increase in field strength causes a rapid rise in electron temperature, as in pulsed discharges.

Capacitive coupling between the lamp and luminaire requires consideration at high frequencies. Although capacitive coupling assists lamp ignition, efficiency is adversely affected during an arc discharge.

Due to the large number of parameters affecting performance it is not possible to accurately predict efficacy gains at high frequency. Experiments conducted, however, suggest a 30% increase in lumen efficacy over mains operation is achievable at 25 kHz.

References

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