OPTIMUM DESIGN BASED ON FIXED FLUX DENSITY AND CONDUCTOR AREA

An approach to the optimum design problem is to consider how a transformer should be designed for minimum cost, given only the following constants.

1. The winding voltages
2. The flux density in the core
3. The cross section of the winding conductor
4. The general type of construction to be used

With modern low-loss iron the flux density in any optimum design can be assumed to be limited, not by iron loss, but by the necessity of maintaining a safe margin below the saturation density in the iron to limit exciting current, or the harmonic content thereof, to reasonable values in event of normal overvoltage. The flux density may also be limited in some types of core construction or other special circumstances by the noise level. There are many circumstances in which these general statements will not be true, but most designers will recognize them to be effective, practical truths, and they will generally agree that reasoning based on the assumption of a constant maximum flux density will give conclusions which will be useful, if not precise and exact. Selection of a flux density is, then, not too difficult.

When the flux density in the core has been selected, the number of turns in the winding is in inverse relation to the cross section of the core; as one goes up, the other must come down. A number of designs of transformers can then be made, but they must inevitably come out with proportions somewhat as shown in Fig. 2-36, where the weight and cost of copper increase with the number of turns, while the weight and cost of iron decrease. The exact shape of the cost curves will vary with all the factors that affect cost. They will be different for different manufacturing methods; hence different for different manufacturers. So many variables affect them that probably no manufacturer knows exactly what the curves are for his particular factory, but it is not necessary to know the exact curve values to know that such curves must exist.

At some value of turns the total cost of core and windings must reach a minimum value, as shown in Fig. 2-36. The total cost of the transformer will be greater than the cost of core and coils, but the minimum value of the total cost will be reached at substantially the same value of turns.

The leakage reactance of the transformer will vary with the turns, as shown in Fig. 2-36. This shows why it will be so expensive to design a transformer with reactance much above or below the standard range of reactance which corresponds to the range of minimum cost.

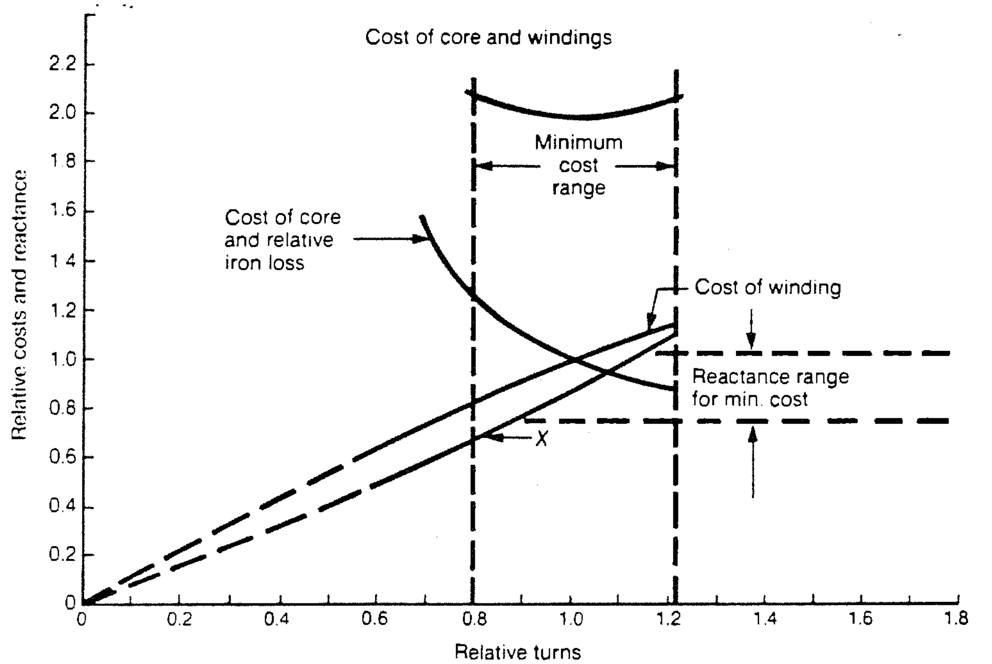

Fig. 2-36 Relative cost, impedance, and losses as functions of the number of turns. (Based on actual computer-design studies of a 15,000-kva three-phase transformer.)

Iron loss will vary with the weight of the iron, also as shown in Fig. 2-36. This shows why it is unreasonably expensive to try to design for low iron loss and low reactance in the same transformer.

The kVA ratings of these transformer designs are still unknown, as are the load loss and efficiency. The transformer has been determined which has minimum cost for the assumed conditions of:

1. Flux density
2. Winding conductor cross section
3. Rated winding voltage

It will have a minimum cost at some value of core cross section and the number of turns in the winding which correspond. Many transformer designs with more cross section of copper in the conductor are possible, and each must have a higher kVA rating. Transformers with smaller cross section of copper and lower kVA are possible, with lower kVA ratings. Evidently one can say that this particular transformer design of minimum cost according to Fig. 2-36 must have some kVA rating which can be determined on the basis of minimum overall operating cost. If the kVA rating is assumed to be higher than the optimum value, the cost of load loss, which varies as the square of load, will be unreasonably high. The cost of cooling the coils can also become unreasonable. If the kVA rating is assumed to be too low, the cost of the transformer per kVA will become too high.

Although actual transformers have been designed to meet certain more or less standard levels of loss and reactance, the basic principle of minimum cost has been in effect over the years, even if the designers did not fully realize it. It is a fair assumption to consider that most transformer designs are actually not too far from the desired optimum value indicated in Fig. 2-36. If this assumption can be accepted, it remains only to determine the optimum kVA loading at which the transformer should be operated.

It will be found in practical examples that the economic loading of transformers is usually at a point where the load loss is from three to six times the no-load loss. The economic loading will be higher where the power for losses is cheap. However, if the load is increased to the higher values, the problem of cooling becomes more and more difficult. The real cost of the transformer will increase by a significant amount because both the coils and external coolers will have to be designed to transfer large quantities of heat to the cooling medium. This means that the transformer design which has the theoretically minimum cost of active materials may not be the one which is quite the optimum when the real cost of cooling is added. Transformers in exceptionally large kVA ratings usually require forced cooling, with a large fraction of their cost going into cooling equipment. A type of coil design such as the interleaved-pancake coil design, which is perhaps more expensive to fabricate, may pay for itself in the ease and effectiveness with which it can be cooled by forced-oil circulation.