The Advantages and Application of Three Winding Transformers

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Abstract

Although seldom used in Australia and New Zealand, three winding transformers reduce costs, losses, fault levels and the size of substations. The paper describes the three options for arranging the windings and the interwinding reactances associated with each option. A sound understanding of the options is needed if three winding transformers are to be applied successfully.

1 Introduction

Although three winding transformers offer a number of advantages, many engineers have tended to avoid them because they are unconventional and believed to be difficult to apply.

Any engineer thinking of using three winding transformers must understand how the transformer designer can adjust the reactances between the three windings. Without this understanding, it is easy to specify transformers that cannot be made or are difficult and expensive to design and manufacture.

This paper is intended to be a simple guide to the technology and application of three winding transformers. It is based on a study carried out by Sinclair Knight Merz for Vector Limited in New Zealand which led to a decision to use 3 winding transformers at a substation in the Auckland CBD.

2 Application

Three winding transformers can be applied in a number of roles in a power system.

For example they can be used in a heavily loaded zone substation to limit fault levels on the lower voltage busbars. For this application, two transformers each with two secondary windings are arranged so that one winding is connected to one lower voltage switchboard and the other winding to a separate switchboard at the same voltage. This limits the fault levels without the need for very high reactance transformers - or twice the number of smaller transformers. This arrangement is common in the UK and Europe.

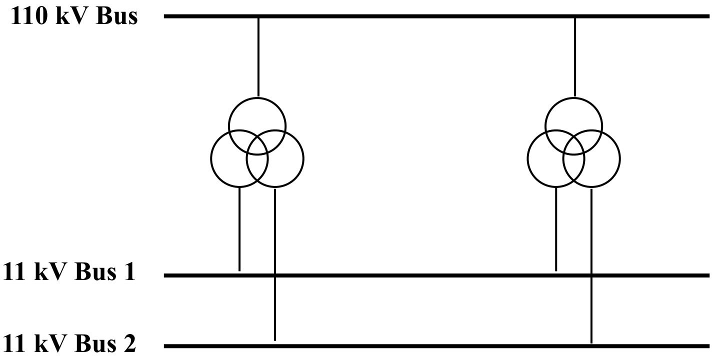

Figure .1 Three Winding Transformers Supplying Two Separate Switchboards

Three winding transformers can also be used at a generating station to connect two relatively small generators to one EHV transformer. This reduces the costs of transformers and EHV switchgear and at the same time limits short-circuit levels on the generator switchgear. To give some idea of the savings, typical values of a 220kV switchgear bay and a 50 MVA 220kV transformer are $750,000 each. Hence, using, say, two 100 MVA three winding transformers instead of four 50 MVA transformers can save more than $1 million.

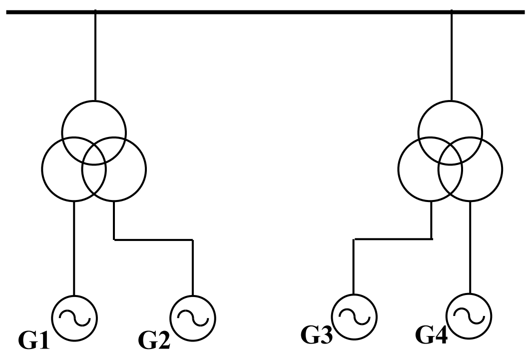

Figure 2. Connecting Generators to EHV Bus Using Three Winding Transformers

A third use is for transformation between three voltage levels so that a transformer connected to an EHV system can supply both sub-transmission and distribution systems. This improves the economics of providing two voltage levels at one substation.

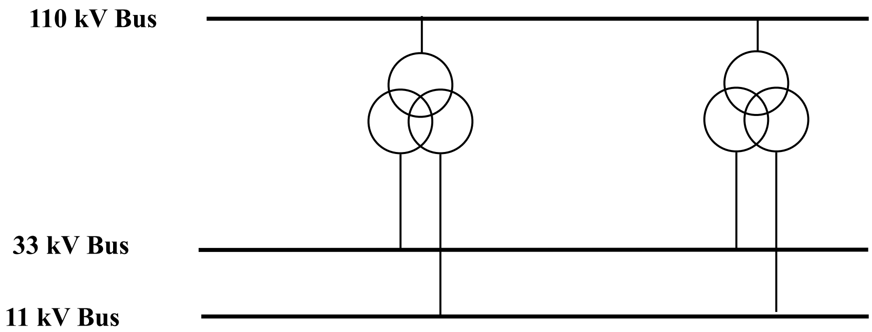

Figure 3. Three Winding Transformers Supplying Sub-Transmission and Distribution Systems

The latter case is directly relevant to 110/33/11kV (or 132/66/22kV) urban distribution. The use of three 3 winding transformers will result in a substantial reduction in the space required in a substation and reduce the cost of the transformers and associated switchgear. Losses will also be reduced because the need to transform from 110kV to 33 kV and then from 33 kV to 11 kV is eliminated.

Three windings are also needed when star/star transformation is used to match phase angles when transforming from 110 kV to 11 kV. A star/star transformer should have a delta tertiary winding to allow zero sequence current to flow in the star windings. The tertiary winding is usually rated at 33% of the transformer rating and is often used for auxiliary supplies or for the connection of a synchronous condenser.

3 Winding Arrangements

There are three options for arranging the windings of three winding transformers.

The effect that these arrangements have on the ratings and reactances of the windings must be understood if three winding transformers are to be applied and specified successfully.

The first option has both the low voltage windings inside the high voltage winding. As a consequence of this arrangement, the reactances between the high voltage winding and the two LV windings must be different and the reactance between the two low voltage windings is relatively small. This is a good arrangement if there is a need to transfer power between the two LV windings. It is a very good arrangement where one winding supplies a 33kV bus and the other an 11kV bus. It is not a good winding arrangement for a power station where the primary objective is to limit the coupling between the two LV windings in order to minimise fault levels.

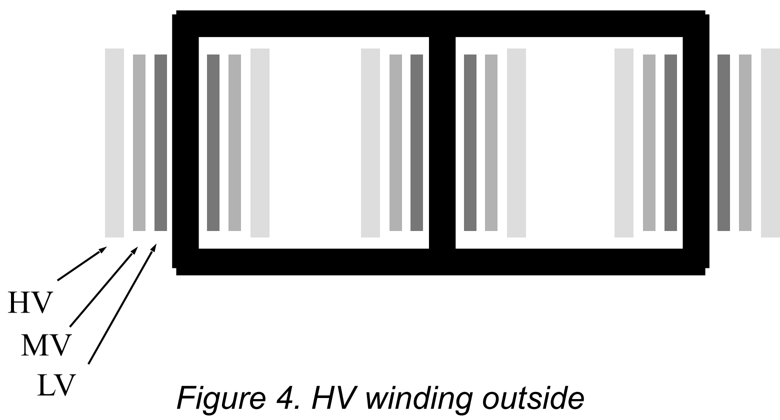

Figure 4. HV winding outside

The second winding option is to have a high voltage winding which is centre fed so that there are effectively two HV windings, one with its neutral end at the top of the transformer and the other with its neutral end at the bottom. The LV windings are stacked one on top of the other, each coupling with one section of the high voltage winding. In order to maintain ampere turn balance the two windings must have identical MVA ratings. This arrangement gives the secondary windings identical reactance, while the reactance between the two low voltage windings is quite high, thus limiting the coupling between them. This is a very good option for limiting fault levels on an 11kV system by splitting the busbars.

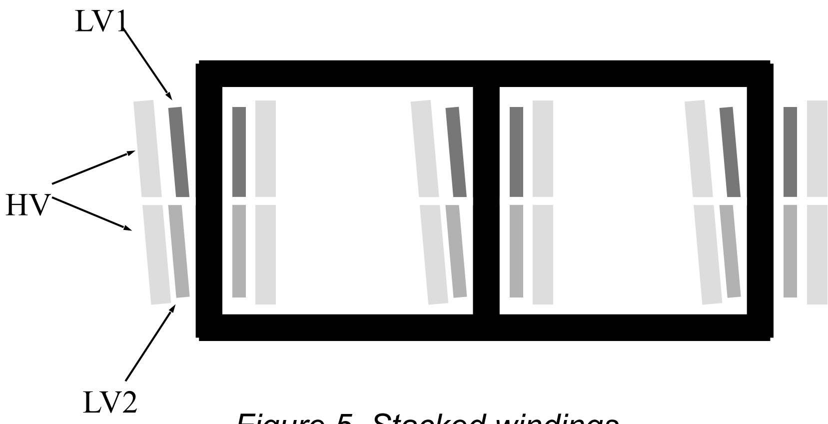

Figure 5. Stacked windings

The third option is to arrange the windings so that one low voltage winding is inside the high voltage winding and the other on the outside. As a result it is possible – within a reasonable range – to specify the reactances of the two low voltage windings independently of each other. The reactance between the two low voltage windings is high. The major disadvantage with this winding arrangement is that it is difficult to bring out the tap changer leads from the high voltage windings because there is little space between the high voltage winding and the low voltage winding which is outside of it. From a transformer designer's point of view, this is the least attractive of the three options, but the problems are not insurmountable and the arrangement is commonly used. It is useful for a 110kV transformer feeding a 33kV and 11 kV system as it can match the need for a low fault level on the 11kV system and a higher fault level on the 33kV system.

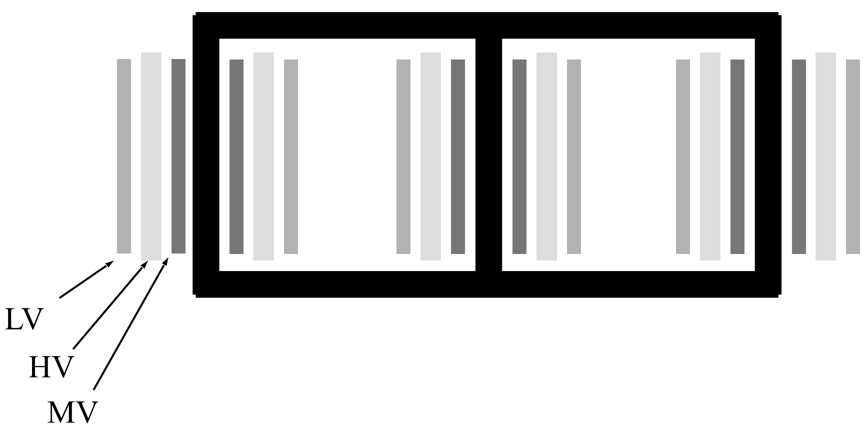

Figure 6. HV winding in the middle

4 Reactances

A typical range of reactances with the above winding arrangements is as follows:

Winding arrangement Reactances	HV-MV Zhm	HV-LV Zhl	MV-LV Zml
LV and MV windings inside HV	8-15%	12-20%	5-10%
Stacked HV winding, identical stacked LV	8-15%	8-15%	40-60%
HV in the middle, MV inside LV outside	8-15%	10-20%	30-50%

The above reactances are based on the rating of the LV and MV windings to give a direct comparison with equivalent two winding transformers. However, when specifying three winding transformers, the convention is that reactances should be based on the rating of the highest rated winding.

For fault level studies and load flows, the equivalent star reactances corresponding to the above interwinding reactances are needed. These can be calculated from the above interwinding reactances by the following formulae:

$$Zh = 1/2(Zhm + Zhl - Zml)$$

$$Zm = 1/2(Zhm + Zml - Zhl)$$

$$Zl = 1/2(Zhl + Zml - Zhm)$$

5 Voltage Control

Three winding transformers complicate voltage control.

With conventional two winding transformers the tap changer normally operates on the HV winding to hold the LV voltage constant.

Normally, a three winding transformer has a tapchanger on the HV winding. The voltage regulating relay is connected to either the LV VT or the MV VT. In most cases, it is the LV (11 kV) voltage that needs to be closely regulated so the voltage regulating relay is connected to the 11 kV VT. Because the windings are on the same core, the MV voltage will also be affected by the tap position and the load on the LV windings. Most of the time the loadings on the LV and MV windings will change together so this should not introduce any problems. Nevertheless it may be wise to consider ±2.5% taps on the 33kV windings - which could be off load switches or simply bolted terminals under oil. This would ensure that there is scope, for instance, for reducing the 33kV voltage in the initial stages before the full 33kV load is imposed on the transformers. However, from a design and manufacturing point of view, taps add complexity and cost so they should be specified only if system studies identify a definite need.

It is possible to have tapchangers on both the lower voltage windings but this adds cost and complexity.

6 Typical Application at a 110/33/11kV Substation

As an example, consider a substation with a 110 kV supply, a 33 kV switchboard supplying a 33 kV sub-transmission load of 50 MVA and a 11 kV system with a load of 30 MVA. The 33 kV fault level must be limited to 1500 MVA and the 11 kV fault level must be limited to 250 MVA.

The conventional solution would be two 110/33 kV two winding transformers each rated at 40/80 MVA and two 33/11 kV two winding transformers rated at 15/30 MVA - a total of 220 MVA of transformer capacity. Two 110 kV circuit breakers, four 33 kV circuit breakers and two 11 kV circuit breakers would be needed. To limit the 11 kV fault level to 250 MVA, the 33/11 kV transformers would need to have a reactance of about 15%.

With 3 winding transformers, the 110 kV winding needs to be rated 40/80 MVA, with 25/50 MVA on the 33kV winding and 15/30 MVA on the 11 kV windings - a total of 160 MVA of capacity. Two 110 kV circuit breakers, two 33 kV circuit breakers and two 11 kV circuit breakers would be needed. So there would be large savings in cost and space.

7 Typical Application at a 220/11kV Substation

Consider a 220 kV substation supplying an 11 kV industrial load of 120 MVA split between two busbars, each with 60 MVA of load.

The conventional solution would be four 220/11 kV 2 winding transformers each rated at 60 MVA. Four 220 kV circuit breakers would be needed. To limit the 11 kV fault level to 750 MVA, the transformers would need to have a reactance of about 16%.

Alternatively, two 120/60/60 MVA 3 winding transformers can be used. This saves $1.5 million worth of 220 kV circuit breakers and at least $500,000 in transformer cost.

The option of two 2 winding 120 MVA transformers with a very high reactance to limit fault levels is not attractive. The high reactances consume expensive reactive power and result in very large secondary voltage drops if one transformer trips out. If this voltage drop makes the load power factor worse, there is a risk of voltage collapse if transformer reactance is greater than about 20%.

8 Cost Estimates

Estimated costs of the installation described in Section 6 with 3 winding and two winding transformers are given below:

Description	No	Unit cost	Installation	Total
THREE WINDING TRANSFORMERS				
80/50/30 MVA Tf	2	$1,300,000	$100,000	$2,800,000
33kV circuit breakers	2	$70,000	$15,000	$170,000
Total				**$2,970,000**
Losses at 50% load - kW	2			500
TWO WINDING TRANSFORMERS				
80 MVA 110/33kV Tf	2	$1,200,000	$100,000	$2,600,000
30 MVA 33/11kV Tf	2	$550,000	$100,000	$1,300,000
33kV circuit breakers	4	$70,000	$15,000	$340,000
Total				**$4,240,000**
80 MVA - Losses at 50% load - kW				450
30 MVA - Losses at 50% load - kW				240
Total losses				**690**
SUMMARY				
Saving in losses kW				**190**
Saving in costs $				**$1,270,000**

9 Conclusions

Three winding transformers offer substantial savings in space, costs and losses.

Although there are limits on the range of reactances that can be used, an engineer with a good understanding of the winding arrangements can halve the number of transformers in most circumstances.

Governments and regulators have signalled their intention to drive down transmission and distribution charges by ensuring that the value is based on an optimised system. In many cases, three winding transformers will be taken to be the optimum solution and installations with a larger number of two winding transformers may suddenly be valued at much less than their cost!