$x_{кз2}$ остаются постоянными. Поскольку полное, активное и реактивное сопротивления короткого замыкания трехфазного двухобмоточного трансформатора равны сумме соответствующих сопротивлений:
$Z_{кт} = Z_{кт\,1} + Z_{кт\,2}$,
$Z_{кз} = Z_{кз1} + Z_{кз2}$, $r_{кт} = r_{кт\,1} + r_{кт\,2}$, $r_{кз} = r_{кз1} + r_{кз2}$, $x_{кт} = x_{кт\,1} + x_{кт\,2}$, $x_{кз} = x_{кз1} + x_{кз2}$,
то полное, активное и реактивное сопротивления короткого замыкания, полученные на основании опыта короткого замыкания трехфазного двухобмоточного трансформатора при схеме соединения первичной обмотки в треугольник, меньше на 2/3 значений фазных сопротивлений первичной обмотки $Z_{кп}$, $r_{кп}$, $x_{кп}$ по сравнению с соответствующими параметрами, полученными при схеме соединения первичной обмотки в звезду: $Z_{кз} – Z_{кт} = 2Z_{кп}/3$; $r_{кз} – r_{кт} = 2\,r_{кп}/3$; $x_{кз} – x_{кт} = 2\,x_{кп}/3$.

Окончательно имеем, что полное, активное и реактивное фазные сопротивления короткого замыкания первичной обмотки в полтора раза больше разности соответствующих параметров, выявленных на основании измерений в опытах короткого замыкания трехфазного двухобмоточного трансформатора при соединении первичной обмотки в звезду, а затем в треугольник: $Z_{кп} = 1{,}5\,(Z_{кз} – Z_{кт})$; $r_{кп} = 1{,}5\,(r_{кз} – r_{кт})$; $x_{кп} = 1{,}5\,(x_{кз} – x_{кт})$.

Параметры полного, активного и реактивного сопротивлений короткого замыкания первичной обмотки трех одинаковых однофазных двухобмоточных трансформаторов могут быть определены по аналогии экспериментально при их соединении в трехфазную группу. Параметры тех же сопротивлений короткого замыкания вторичной обмотки двухобмоточного трехфазного трансформатора и любой обмотки многообмоточных трехфазных и однофазных трансформаторов находятся точно так же, превращая ее в первичную.

ВЫВОДЫ

Проведенное экспериментальное исследование демонстрирует определенные закономерности при раздельном измерении полных, активных и реактивных сопротивлений обмоток трансформаторов. Измерялись линейные токи и напряжения, а также мощности в опыте короткого замыкания трехфазного двухобмоточного трансформатора или группы из трех одинаковых двухобмоточных однофазных трансформаторов при схемах соединения их первичных обмоток сначала в треугольник, а потом в звезду. По значениям мощности трех фаз, средних линейных значений напряжения и тока опыта короткого замыкания вычислены сопротивления короткого замыкания при схемах соединения питающей обмотки в те же треугольник и в звезду. В 1,5 раза увеличенные их разности, полученные для схем соединения первичной обмотки в звезду и в треугольник, и есть полное, активное и реактивное сопротивления питающей обмотки трехфазного трансформатора или группы из трех одинаковых однофазных трансформаторов. Параметры подобных сопротивлений любой обмотки многообмоточных трехфазных и однофазных трансформаторов могут быть определены аналогично, превращая их в питающие.

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MEASUREMENT OF TRANSFORMER WINDINGS RESISTANCE

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ABSTRACT

The article contains a theoretical rationale and describes the method of separate measurements of total, active and reactive resistance of transformer windings. Linear currents and voltages are measured, as well as power in the short-circuit experiment of a three-phase two-winding transformer or group of three identical two-winding single-phase transformers. From the values of the three phase power, average linear voltage and current values of short circuit resistance are calculated in delta and wye connection

schemes of supply windings. Parameters of total, active and reactive resistance by short-circuit of any winding of multiwinding three-phase and single-phase transformers can be defined similarly, turning them into supply windings.

ENGLISH SUMMARY

Background. *Currently total, active and reactive resistances of the primary and secondary windings of the transformers are not measured separately [1–4 etc.]. It is assumed that resistances with the same number of turns, are noticeably equal to each other, and equal to half of the resistance of transformer in the short-circuit experiment. For a more accurate value of the circulating current in parallel operation of three-phase transformers of 12 and 11 groups of winding connections it is necessary to have values of total resistances of their primary and secondary windings [5].*

It is proposed to measure the parameters of three-phase two winding transformers in the short- circuit experiment with the use of conventional instrumentation initially with the scheme of delta connection of the primary winding (Pic. 1), and then – wye connection (Pic. 2).

Objective. *The author strives to demonstrate separate measurements of total, active and reactive resistance of transformer windings.*

Method. *The study was conducted with the use of short-circuit experiment and mathematical calculations.*

Results. *Pic. 1 and 2 show that the secondary windings 5 and 7 of the three-phase two-winding transformer, which are wye-connected are short-circuited. In wires, the primary supply windings of which are delta- (Pic. 1) and wye- connected (Pic. 2), three identical ammeters RA 1, two identical power meters PW 2 and three identical voltmeter PV 3 are on.*

Separate measurement of total, active and reactive resistance of the primary and secondary windings of a three-phase two-winding transformer is as follows. In a short -circuit experiment the secondary windings 5 and 7, which are wye-connected (Pic. 1 and 2), are short-circuited, and to the primary windings 4 and 6 reduced linear voltage $U_к$ *is added, whereby the primary linear current* $I_к$ *is equal to the nominal value* $I_н$*. For three-phase two-winding transformer short-circuit power of the three phases* $P_к$ *is defined on the basis of the algebraic sum of readings of two wattmeters PW 2, and the average values of the linear voltage* $U_к$ *and linear current* $I_к$ *are calculated on the basis of the readings of three voltmeters PV 3 and one ammeter RA 1.*

When the primary supply winding 4 of three-phase two-winding transformer 4 is delta- connected (Pic. 1) phase short circuit parameters are:

– total short-circuit resistance

$z_{\text{кт}} = \sqrt{3}U\text{к}/I\text{к}$;

– active short-circuit resistance

$r_{\text{кт}} = P_к/I_к^2$;

– reactive short-circuit resistance

$x_{\text{кт}} = \sqrt{(z_{\text{кт}}^2 - r_{\text{кт}}^2)}$.

When the primary supply winding 6 is wye-connected (Pic. 2), phase short-circuit parameters are:

– total short-circuit resistance

$z_{\text{кз}} = Uk/(\sqrt{3}I\text{к})$;

– active short-circuit resistance

$r_{\text{кз}} = P_к/(3I_к^2)$;

– reactive short-circuit resistance

$x_{\text{кз}} = \sqrt{(z_{\text{кз}}^2 - r_{\text{кз}}^2)}$.

Resistance of the primary winding of the transformer at its delta connection $Z_{\text{кт}\,1}$, $r_{\text{кт}\,1}$, $x_{\text{кт}\,1}$ *is 3 times less than by wye connection* $Z_{\text{кз}1}$, $r_{\text{кз}1}$, $x_{\text{кз}1}$ *and values of the same resistance of the secondary winding* $Z_{\text{кт}\,2}$, $r_{\text{кт}\,2}$, $x_{\text{кт}\,2}$ *и* $Z_{\text{кз}2}$, $r_{\text{кз}2}$, $x_{\text{кз}2}$ *remain constant. Consequently, the resistance obtained by delta connection scheme of the primary winding is less than 2/3 of the values of the phase resistance of the primary winding* $Z_{\text{кп}}$, $r_{\text{кп}}$, $x_{\text{кп}}$ *as compared with the corresponding parameters obtained on the basis of short-circuit experience with the use of wye connection scheme for the primary winding:*

$Z_{\text{кз}} - Z_{\text{кт}} = 2\,Z_{\text{кп}}/3;\; r_{\text{кз}} - r_{\text{кт}} = 2\,r_{\text{кп}}/3;\; x_{\text{кз}} - x_{\text{кт}} = 2x_{\text{кп}}/3.$

Finally, total, active and reactive phase short circuit resistances of the primary winding are half as much as the difference of corresponding parameters, calculated on the basis of measurements taken in short-circuit experiments of the three-phase two -winding transformer, when the primary winding is wye- connected and then delta-connected:

$Z_{\text{кп}} = 1,5\,(Z_{\text{кз}} - Z_{\text{кт}});\; r_{\text{кп}} = 1,5\,(r_{\text{кз}} - r_{\text{кт}});\; x_{\text{кп}} = 1,5\,(x_{\text{кз}} - x_{\text{кт}}).$

Short- circuit resistance parameters of the primary winding of three identical single-phase two- winding transformers can be determined experimentally, if they are similarly connected in a three-phase group. Short-circuit resistance parameters of the secondary winding of the two- winding three-phase transformer and any winding of multiwinding transformers can be defined similarly, when it is converted into a supply winding.

Conclusion. *The conducted experimental study demonstrates particular regularities in the separate measurement of total, active and reactive resistances of the transformer windings. Linear currents and voltages were measured, as well as power in the short-circuit experiment of a three-phase two-winding transformer or group of three identical single-phase transformers when their primary windings were first delta- and then wye-connected. Using values of three phases power, average linear voltage and current of short- circuit experiment short-circuit resistance was calculated, when the supply winding was delta- and wye- connected. 1.5 times increased differences, which were obtained, were total, active and reactive resistances of the supply winding of a three-phase transformer or a group of three identical single-phase transformers. Parameters of such resistances of any winding of multiwinding three-phase and single-phase transformers can be defined similarly, if they are converted into supply windings.*

Keywords: single-and three-phase, two-and multiple winding transformers, supply winding, total, active and reactive resistance, delta and wye connection.

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