Technical economic analysis concerning connection groups of distribution transformers in Bulgaria

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***Abstract*—In Bulgaria's electricity distribution system, there are over forty thousand power transformers in operation. This article deals with the types of connection of three phase distribution transformer windings and the behavior of the transformer under highly asymmetric loads and emergency modes in low-voltage networks. Transformers with Dyn connection are the most common in distribution networks in our country. Small group of transformers with power of up to 100 kVA are produced with Yzn connection, all other groups of transformers with power above 100 kVA are with Dyn connection. This distinction/separation is introduced due to the fact that small power transformers often operate in modes with large asymmetry of the phase loadings. The increase in loads and the inclusion of more and more non-linear loads in the networks require a change in this separation criterion. In this article, the behavior of transformers from the two main types of connection of windings under the influence of asymmetric currents and short circuits in low-voltage networks is analyzed. A techno-economic analysis of the profitability of the two main connection types under conditions of different loading has been performed and we propose a model for determination of the type of transformer connection according to the prevailing mode of operation of low voltage networks. Examples are presented and discussed.**

***Keywords*—transformer, type of transformer windings connection, short circuit, power quality, imbalance propagation.**

I. INTRODUCTION

Modern distribution networks feed mainly single-phase consumers, which causes asymmetric operation mode and flow of reverse and zero-sequence currents, which adversely affect the quality of electrical energy, the level of electrical energy losses, the operational life cycle of transformers, motors, etc.[1]. The distribution companies accept a low voltage of up to 15% as an acceptable current asymmetry in the networks. The main element of the electrical network that distributes the unbalance currents is the transformer. The type of connection of the windings in the transformer determines the behavior of the currents and voltages in asymmetric and emergency modes of operation.[2] In scientific literature sources, the type of vector connection groups of transformers in distribution networks is recommended to be matched with the connection group of step-down transformers in HV/MV substations in order to neutralize the load angle. For example, if the step-down transformer in a HV/MV substation has vector group Ynd11, respectively, for the distribution transformers fed by this substation, it is recommended that the connection vector group for transformers with a power of more than 250 KVA be connected type Dyn1, for small transformers with a power of less than 250 kVA the bonding must be Yzn5 type.[3] In the distribution networks in our country, transformers with power from 100 kVA to 800 kVA have a Dyn connection. All ranges of transformers up to 100 kVA, due to operation in modes with greater asymmetry and emergency situations have Yzn connection.[4] Such a division is indicated in the BDS standard EN 50708-1-1:2020, and on this basis, the distribution companies have developed internal standards in which the purchased new transformers are divided by power into these two main groups. Contemporary realities show that such a division is outdated and does not contribute to improving the profitability and reliability of the system. The increase in household loads, the growth of settlements and the deterioration of quality, leads to an increase in the nominal power of transformers, thereby significantly reducing the number of small power transformers Yzn in the system. At this moment, only 10% of all transformers in Bulgarian distribution networks have a capacity of up to 100 kVA, whereas 15 years ago, this percentage was 17%. The reliability of electrical networks largely depends on the selection of a suitable transformer. The determination of the connection group must be taken into account along with the operation conditions, the load schedule, the climatic region, the specific fed consumers and the emergency situation in the respective region. The maximum percent value of voltage unbalance shall be within 2% during 95% of the measurement period.[5] The most common cases of asymmetry in practice are a single-phase short circuit between the phase and neutral conductor in low-voltage networks, and an emergency disconnection of a phase from the supply voltage of the primary winding in the transformer. In the place of the imbalance, reverse and zero-sequence components appear, which lead to overheating of the rotors of the synchronous generators, an increase of the losses in the neutral conductors and disturbances in the protection systems.[6]

II. PROBLEM FORMULATION AND MODEL DESCRIPTIONS

An analysis of the behavior of the two main groups of transformers in different emergency situations in distribution networks fed by transformers with connection Dyn and the second with transformer Yzn will bring clarity to the current problem.

- **Transformers with Dyn connection**

Distribution transformers with vector connection group Dyn represent the main group (about 90%) of all distribution transformers in operation in our country. The widespread use of this type of connection is due to the advantages associated with zero-sequence currents. No earth current I_E caused by an earth fault or an unbalanced load in the distribution network

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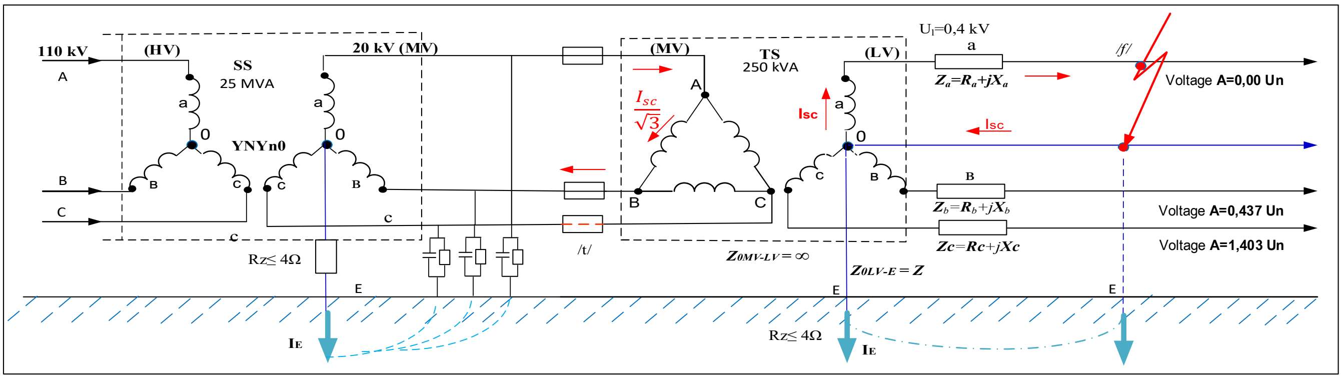

Fig. 1. short circuit in a vector group Dyn distribution network

will flow between the primary and secondary windings due to the infinitely large impedance.

$$\mathbf{Z_0}_{MV\text{-}LV} = \infty. \quad (1)$$

Thus, the third harmonic current is retained only in the delta connected winding.[7] All harmonics and zero-sequence currents close the circuit only within the boundaries of the transformer windings. In this way, the odd harmonics produced by the magnetizing current do not increase the temperature of the transformer terminals and do not cause additional losses.[8] In transformers where there is no retention and third and other harmonics appear in the secondary winding, losses can rise to 28% .[9] In addition, this type of transformer connection has a relatively simplified construction and low metal costs, due to the fact that only $\frac{1}{\sqrt{3}}$ times the phase current flows through the primary windings, which leads to a small cross-section of the wires and, accordingly, a small area of the coil.[10] With these advantages, the Dyn connection is an ideal option for all power transformer ranges. To analyze the behavior of Dyn in emergency situations we will consider an example with a short circuit between phase A and neutral conductor illustrated on fig.1 In case of a short circuit at point /f/, the short circuit current Isc will flow through the neutral wire and part of it through the ground to close the circuit. In one of the primary windings of the transformer, winding A-C will flow some of the short-circuit current, which will produce two currents equal in magnitude and opposite in direction. This will de-balance the voltages in the grid. The dependences of the impedances in this case will be:

$$\mathbf{Z}_a=0\ ;\ \mathbf{Z}_b=\mathbf{Z}_c=\infty \quad (2)$$

In one of the healthy phases in the low voltage network / in this case phase C / the voltage will rise to 1.403 Un. On Phase B the voltage will drop to 0.437 Un. According to IEC 60909, the overvoltage values of the unfaulted phases with a directly earthed star center should be in the order of 1.38 to $\sqrt{2}\ U_n$. [11] In this case, consumers connected to these phases after the short circuit will suffer material damage, and distribution companies pay significant financial resources for burnt appliances and poor quality. In addition, due to the fact that in our country, in over 90% of all substations, the protection is mainly with high-power fuses, it is possible to maintain the short-circuit current for a long time. This, in turn, leads to increased technical losses of electricity, breaking of insulation, and many other negative consequences. Another common emergency in operation is the Interruption of one of the medium voltage phases feeding the primary windings of the transformer, in this case phase C fig.1. Such an interruption is most often due to a blown medium-voltage fuse or a blown bridge connection. Operation of the transformer in this position will result in the appearance of three highly unbalanced voltages on the secondary side. Only in one of the phases we will have a nominal voltage, and in the other two the voltages will be lowered, respectively phase B by Un/√3 and phase C by Un/2√3. This results in problems for the consumers remaining in the two problem phases, and for the distribution companies.

- **Transformers with Yzn connection**

In the Yzn compound, each secondary winding is divided into two equal parts where the end of each half of the winding on one core is connected to the end of a winding located on another core, and the ends of the first group of windings form a symmetrical star. The low-voltage networks in our country work with a directly grounded star center, providing an easy path for zero-sequence currents. Thus, the zero-sequence currents cancel each other out. This type of connection preserves the magnetic balance in an unbalanced load and reduces the voltage unbalance. The dependences of the impedances at Yzn are:

$$\mathbf{Z_0}_{MV\text{-}LV} = \infty$$
$$\mathbf{Z_0}_{MV\text{-}E} = \infty \quad (3)$$
$$\mathbf{Z_0}_{LV\text{-}E} = 1.Z$$

The zigzag connection provides a low earth current impedance I_E, which provides more reliable overload protection.[12,13] This vector coupling group has many advantages over other couplings when applied to supply low voltage networks, especially in highly unbalanced and emergency situations. In the event of an identical emergency situation of the considered short circuit between phase A and the neutral conductor, the voltage levels of the two healthy phases remain close to the nominal ones, with relatively small deviations from the standard voltages.

$$\mathbf{U}_A=0,\ \ \mathbf{U}_B=0{,}8.\mathbf{U}_N,\ \ \mathbf{U}_C=0{,}94.\mathbf{U}_N \quad (4)$$

These dependencies give Yzn the huge advantage of protecting consumer equipment from burning out after a short circuit. This fact determines transformers with vector group Yzn to work in areas with long overhead lines, where the probability of frequent short circuits is high.[14] The other common in-service emergency is a medium voltage phase failure In such a situation, when connecting Yzn, the operation of the transformer continues in emergency mode

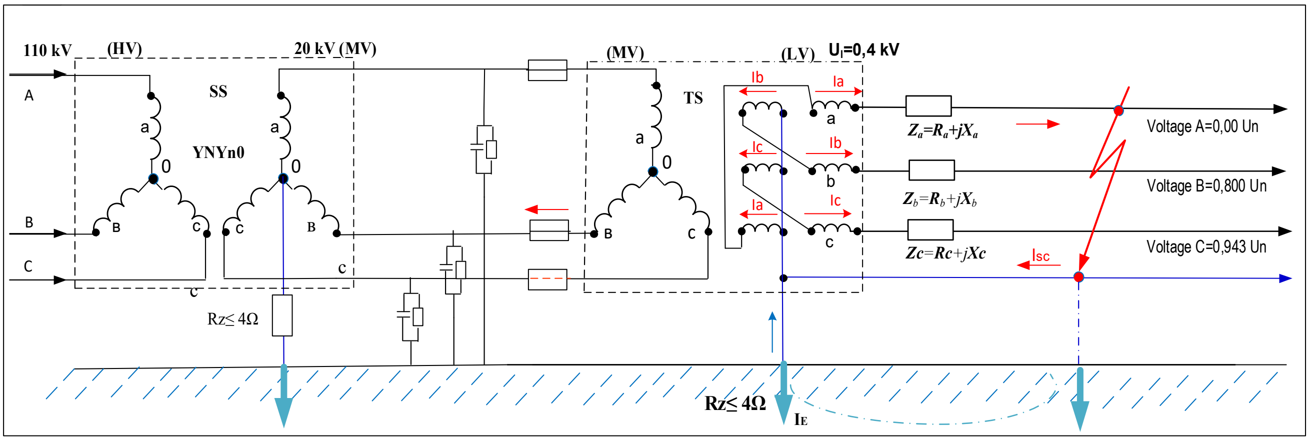

Fig. 2. hort circuit in a vector group Dyn distribution network

where one of the phases is low voltage with rated voltage and the other two phases have the same voltages reduced by √3.[15] The advantages of the Yzn transformer make it the best option for transformers with power up to 250 kVA in distribution networks operating in conditions of large asymmetry and frequent short circuits. The production of transformers with a Yzn scheme with a power of more than 250 kVA is not profitable due to the complex construction, large overall dimensions and increase in costs.[16] The examined examples of the influence of emergency situations in the distribution networks of the two main connection types on the quality of electrical energy show the importance of the transformer connection type on the behavior of the transformer.[17] Distribution companies are limited in their choice, due to the divisions mentioned above and lack of internal instructions and methods for selecting transformers according to the mode of operation.[18,19] The now existing division is not cost effective due to the new realities. The best solution is to select the connection type of the transformer according to the operating mode.

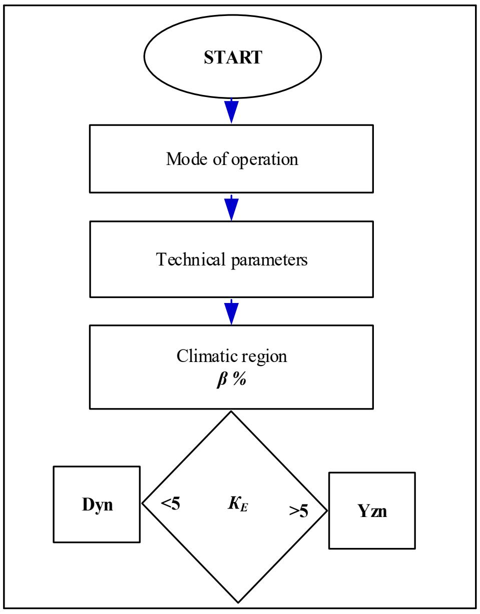

Fig. 3. Connection type determination algorithm

To facilitate the distribution companies in determining the type of connection of the transformer, we offer a technical-economic model for choosing the type of connection of distribution transformers of up to 250 kVA supply in distribution networks, by determining the coefficient of profitability K_E. The coefficient of profitability is determined by the main factors affecting the operating mode of the transformer. These are the technical parameters of the network, the climatic region of the supplied distribution network and the peculiarities of the terrain through which the electrical network passes.

$$K_E = K_S + K_{Teh.par} + S_{route} \quad (4)$$

where: K_S depends on the mode of operation of the distribution network:

Modes of operation in low-voltage distribution networks can be divided into two main groups. The first group are networks with load asymmetry > 20%. Usually these are networks supplying single-phase consumers in settlements with seasonal consumption of electricity /cottage areas, remote hamlets, remote neighborhoods, etc./ $K_S > 20\% = 2$

The second group are networks with a symmetrical load. These are distribution networks supplying single three-phase users such as water pumps, fish farms, small industry users, etc. For these users, despite the small powers, it is economically expedient to use the power transformer with vector group Dyn. $K_S < 20\% = 1$

$K_{Teh.par}$ - Characterizes the technical parameters of the distribution network.

Technical parameters of distribution networks are type of conductors, length of the network and the kind of surrounding environment.

$$K_{Teh.par} = k_c + k_l + k_e \quad (5)$$

where: k_c - The type of conductor is important due to the fact that when the network is realized with twisted insulated wire the possibility of short circuits is limited. Table 1 shows the respective values for AC wire and NFC wire.

k_l - length of the longest low voltage lead from the transformer to the end user. A large part of the networks in our country exceed a length of 1000 m. For such networks **k_l=1.**

k_e - the kind of environment through which the route of the electrical network passes. When passing through a wooded area, the risk of emergency short circuits is greater and then k_e **=1** When the wires pass through an urbanized area, agricultural plantations, fields, etc. the environmental coefficient k_e **=0,3**.

TABLE I. COMPONENT VALUES CONCERNING TECHNICAL PARAMETERS $\boldsymbol{K_{TEH.PAR}}$

$\boldsymbol{k_c}$		$\boldsymbol{k_l}$		$\boldsymbol{k_e}$	
wire type ***AS***	*wire type* ***NFC***	*Length L>1000м*	*Length L<1000*	*Forest*	*Urban environment*
1	*0,2*	*1*	*0,5*	*1*	*0,3*

$\boldsymbol{S_{route}}$ - climatic region of the distribution network. The climatic region is important for the transformer, due to the fact that the greater the icing on the conductors, the greater the probability of emergency short circuits.

TABLE II. DEPENDENCE ON CLIMATIC REGION FOR PARAMETERS $\boldsymbol{S_{ROUTE}}$

Climatic region	II	III	IV	Is	IIs
$\boldsymbol{S_{route}}$	0,5	0,8	1	1,5	2

EXAMPLE

Example 1. To determine the type of connection group of a distribution step-down transformer with a capacity of 250 kVA supplying a cottage area. It is planned that the mode of operation will be with an asymmetry >20%. The distribution network is built with AC wires with a length of 1500 m. The route of the network passes through a forested area in the III climatic region.

Solution: According to $K_E = K_S + K_{Teh.par} + S_{route}$

1. We determine $\boldsymbol{K_{Teh.par}}$ $K_{Teh.par} = k_c+k_l+k_e$

from Table 1 $\boldsymbol{K_{Teh.par}} =$ 1+1+1=3

2. We determine $\boldsymbol{K_E}$

$\boldsymbol{K_E}$ = 2 +3 + 0.8 =5.8 >5 We define the transformer to be of connection group **Yzn**.

With the now existing division of this network, a transformer with Dyn connection had to be installed. With him, the company's financial costs for the purchase would be less by about BGN 2,000, but the company would spend tens of thousands of BGN during the life cycle of this transformer from complaints about poor quality and burnt appliances.

Example 2. To determine the type of connection of a transformer with a power of 63 kVA powering a three-phase motor / water pump. The distribution network is built with NFC wires with a length of 500 m. The route of the network passes through a forested area in the III climatic region.

Solution:

According to $\boldsymbol{K_E} = K_S + K_{Teh.par} + S_{route}$

1. We determine $\boldsymbol{K_{Teh.par}}$ $K_{Teh.par} = k_c+k_l+k_e$

from Table 1 $\boldsymbol{K_{Teh.par}} =$ 0,2+0,5+0,3=1

2. We determine $\boldsymbol{K_E}$ $\boldsymbol{K_E} =$ *1 +1,7 + 0,8* ***=3,5< 5*** We determine the transformer to be with connection group ***Dyn.***

This transformer will operate in balanced load mode and there is no need to place there an expensive Yzn transformer. With this decision, the distribution company will save BGN 1,800 from the purchase price of a transformer with Yzn connection, and in the next 35 years there will be no costs related to emergency conditions and unbalanced load.

CONCLUSIONS

Distribution companies are investing huge sums in improving the reliability of distribution networks. However, complaints from consumers about poor quality, burnt appliances and lost benefits are also on the rise. The connection type of the windings of distribution transformers is of great importance for the quality of electrical energy. For the most frequently induced emergency conditions in distribution networks, and for asymmetrical operating modes in medium voltage and low voltage power lines, the best solution is a vector connection group Yzn. It is economically expedient for distribution companies in order to improve quality indicators for consumers to implement the proposed model instead of using the current division for connection groups. It is necessary for the distribution companies to change their standards for the purchase of new transformers, taking into account the peculiarities of the distribution network for which the transformer is intended. It is profitable to purchase transformers of up to 250 kVA with connection group Yzn. This could guarantee a small imbalance of the voltages and a quick action of the protective devices in the substation. However, due to the higher cost and large dimensions, Yzn connection is not recommended for power ranges above 250 kVA.

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