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The Effect of Transformer's Vector Group on Retained Voltage Magnitude and Sag Frequency at Industrial Sites Due to Faults

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Abstract**—**This paper deals with the effect of a power transformer's vector group on the basic voltage sag characteristics during unbalanced faults at a meshed or radial power network. Specifically, the propagation of voltage sags through a power transformer is studied with advanced short-circuit analysis. A smart method to incorporate this effect on analytical mathematical expressions is proposed. Based on this methodology, the positive effect of transformers of certain vector groups on the mitigation of the expected number of voltage sags per year (sag frequency) at the terminals of critical industrial customers can be estimated.

Keywords**—**Balanced and unbalanced faults, industrial design, phase shift, power quality, power systems, voltage sags (or dips).

I. INTRODUCTION

VOLTAGE sags are rapid drops in the rms voltage and are mainly caused by short-circuits in the electric power transmission or distribution system. They are characterized by the remaining (retained or during-fault) voltage magnitude. Short-circuits give the most severe sags and their consequences on sensitive equipment, such as computers, adjustable speed drives or control devices, can be significant. Voltage sags are as critical as voltage interruptions for common industrial sites, which are more severe but less frequent. The sensitivity of equipment and sag frequency (annual number of sags) causes financial losses that may be enormous for some industrial customers.

Several mitigation methods for the consequences of sags and other power quality phenomena have been proposed [1]-[3]. A proper selection of the power transformer carrying the electric power from the transmission to the distribution system is a common way used by the electric utilities to mitigate voltage sags caused by unbalanced faults and, especially, the one-phase-to-ground faults which are the most frequent. The transformer's vector group determined by winding connections and phase displacement applied on instant voltages is a low-cost and effective way to significantly mitigate the severity and frequency of voltage sags. The propagation of sags through power transformers of different winding connections and phase shifts is also discussed in [3]-[6].

Moreover, the first step for the selection of the appropriate mitigation method after the transformer's vector group has been determined is the assessment of the expected number of sags per year. Three methods have been proposed for the assessment of voltage sags due to faults: the method of Critical Distances [7]-[9], the method of Fault Positions [10], [11] and the Monte Carlo method [12]. All methods combine the response of the system to faults with stochastic data.

In this paper, the effect of transformer's vector group on the propagation of voltage sags, retained voltage magnitude and sag frequency is studied. Advanced analytical expressions for the calculation of voltage sag magnitude in case of symmetrical (balanced) or asymmetrical (unbalanced) faults [7] are used to quantitatively study the effect of a Delta-Wye (D-Y) connected power transformer with a certain phase shift. A method to incorporate this phase shift on analytical expressions giving the sag magnitude due to unbalanced faults is provided.

II. TRANSFORMER'S VECTOR GROUP AND CONNECTIONS

The related terminology for vector groups and winding connections of power transformers together with common (or preferred) connections are described in international standards such as IEC [13] or IEEE [14], [15]. "Vector group" is a term proposed only by the IEC standards and by transformer manufacturers until now. It denotes the way in which the windings are connected and the phase position of their respective voltage vectors. It consists of:

1) Letters identifying the configuration of the phase windings. In three-phase ac systems, winding connections are categorized as Delta (D, d), Star or Wye (Y, y), Interconnected star or zigzag (Z, z) and Open or Independent (III, iii) windings [13]. Capital letters relate to the High-Voltage (HV) windings, lower-case letters to the Medium-Voltage (MV) and Low-Voltage (LV) windings. The vector group begins with the capital letter.
2) A letter (N, n) which indicates that the neutral of a winding in star or interconnected star is brought out.
3) A number indicating the phase displacement between the voltages of the windings taking as a reference the HV winding. This number, multiplied by 30^0, denotes the

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angle by which the vector of the LV winding (phase voltages) *lags* that of the HV winding. The angle of any LV winding is conventionally expressed by the 'clock notation', that is, the hour indicated by the winding phasor when the HV winding phasor is at 12 o'clock (rising numbers indicate increasing phase lag). Common three-phase transformer connections (with no reference to the neutral point of the star-connected windings) according to IEC 60076-1 are presented in Table I.

For example, a transformer with a vector group of Dyn1 has a delta-connected HV winding and a wye-connected LV winding with its neutral point brought out. The angle of the LV winding phase voltages lags the HV by 30^0. Moreover, a transformer with a star-connected HV winding having its neutral ungrounded, and a delta-connected LV winding with 330^0 lagging (or 30^0 leading) angular displacement, is denoted as Yd11.

In [16], [17], there are some interesting points and criteria for the selection of transformer's vector group. Elimination of harmonics, earth fault currents, neutral stabilization and type of application (transmission or distribution system, connection of a generator, power electronic converter, industrial load etc) are the most common criteria.

However, the positive effect of transformers of certain vector groups on the mitigation of voltage sags (or dips) is not thoroughly studied in the literature. This paper presents an attempt to confirm and quantify this effect and other characteristics related to sags (or dips).

III. SAG MAGNITUDE CALCULATION USING FAULT ANALYSIS

Voltage sag magnitude, which is the minimum retained (or during-fault) voltage among the three phases, can be calculated using analytical expressions derived from short-circuit theory [6] or performing detailed simulations [4], [5]. In [1], [2] simplified expressions based on the voltage divider model have been proposed for fast assessment of the critical distances and the number of sags. This approach is suitable for radial networks but presents many limitations for meshed systems [10], [11].

For a more accurate calculation of voltage sag magnitude and phase-angle jump, it is important to use advanced analytical expressions for the sag magnitude due to symmetrical and asymmetrical faults that are applicable to meshed and radial power networks. The methodology and the analytical expressions for the sag magnitude of the examined sagged node in relation with the fault distance due to faults at every point of a power line are given in [7]. These expressions take into account pre-fault voltage, fault impedance, reactance but also resistance of power system components. A set of mathematical equations is provided when the position at which the sag magnitude is calculated is at the same or at different voltage level with the fault position.

IV. EFFECT OF POWER TRANSFORMER VECTOR GROUP

A. Adjustment of Bus Impedance Matrices

In case of three-phase (3ph) faults, the power transformer's vector group has no effect on remaining (during-fault) phase voltages and sag magnitude. In case of asymmetrical (unbalanced) faults, the transformer's vector group should be taken into account and proper modifications in the analytical equations giving during-fault rms phase voltages should be done. These modifications include the adjustment of zero-sequence bus impedance matrix which is related with the winding connections. Moreover, the phase displacement (if any) introduced by the transformer should be incorporated into the analytical equations. For example, a Dy1 (or Yd1) transformer introduces a phase displacement of -30^0 in the positive-sequence voltage and a $+30^0$ in the negative-sequence voltage when passing through this transformer from the HV to the LV winding, which is also applies for the fault currents [18]. Thus, a phase shift of $+60^0$ in the negative-sequence voltage can be applied, which is finally applied at the negative-sequence transfer impedance Z_{kf} of buses at HV (bus *k*) and LV (bus *f*) winding [7], [9]. Similarly, a phase shift of -60^0 in the negative-sequence voltage should be applied when a fault occurs on the LV side and observed by a node on the HV side as shown in Fig. 1.

TABLE I
COMMON CONNECTIONS ACCORDING TO IEC 60076-1 [13]

Number	Connections	Number	Connections
0	Yy0, Dd0, Dz0	2	Dd2, Dz2
1	Yd1, Dy1, Yz1	4	Dd4, Dz4
5	Yd5, Dy5, Yz5	7	Yd7, Dy7, Yz7
6	Yy6, Dd6, Dz6	8	Dd8, Dz8
11	Yd11, Dy11, Yz11	10	Dd10, Dz10

B. Effect on During-Fault Voltages and Sag Magnitude

The phase displacement introduced by transformers of certain vector groups will also affect the characteristics of the during-fault voltages and the sag magnitude. This happens when faults occur at the other side of a transformer from which the during-fault voltages are calculated. Specifically, two-phase (2ph) and two-phase-to-ground (2ph-g) faults result in only one sagged phase and one-phase-to-ground (1ph) faults result in two sagged phase voltages.

In Fig. 2, the sag type (number of sagged phases) and the particular sagged phase (in brackets) can be found for an asymmetrical fault between particular phases (also in brackets) on the other side of the transformer. The direction of the arrow shown in Fig. 2 is proved to be valid for vector groups with a number of 1 or 7. The opposite direction for this arrow applies for vector groups of 5 or 11, which means also that different phases give the sag magnitude in relation with the previously mentioned vector groups.

The most interesting effect of transformers with vector group of 1, 5, 7 or 11 is related with the sag magnitude, which is the minimum among the three during-fault phase voltages. The sag magnitude at one side of the transformer is equal for either 3ph, 2ph-g or 2ph faults on the other side of the transformer. Only 1ph faults give different sag magnitude. This was proved in [9] using the mathematical equations derived for the during fault calculation and by incorporating the effect of transformer's vector group on zero- and negative-sequence bus impedance matrices as described in Section IV.

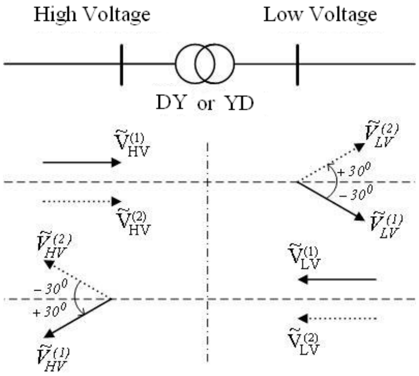


Fig. 1 Effect on positive- and negative-sequence voltage vectors

It should be noted that this applies for a zero fault impedance and equal positive and negative bus impedance matrices, which are common assumptions used in short-circuit analysis.

C. Effect on Sag Frequency

Sag frequency is the expected number of sags of a certain magnitude per year. It is estimated by combining calculation data regarding the sag magnitude with stochastic data related with the fault rate and type.

We will now examine the effect of transformers with vector group number of 1, 5, 7 or 11. It can be proved that for those transformers, when 1ph faults occur at one side, two phases at the other side are sagged but the sag is less severe. For 2ph faults, the opposite occurs: One phase is sagged at the other side of the transformer and the sag is more severe. For 2ph-g faults, one phase is sagged but the severity is equal at both sides of the transformer and equal with that resulted from 3ph faults. As 1ph faults are the most frequent with a probability of more than 70% and the 2ph faults rarely occur, sag frequency will be much lower due to this type of transformers.

V. STUDY CASE

Voltage sag assessment is mainly important for industrial customers and usually is performed in distribution networks. For a more accurate assessment, the contribution of faults at the transmission network feeding the distribution network should not be ignored. Therefore, a suitable power network for the application of a voltage stochastic assessment method is as the one shown in Fig. 3. Six industrial customers are connected at six nodes of the same 20 kV distribution line hrough a solidly grounded Dyn1 transformer, widely used in Greece. The equivalent transmission system consists of three 150 kV lines and is relatively of large size to take into account the fact that faults even at hundred kilometers away from the critical customers will cause them severe sags [3].

A. Sag Magnitude of MV Nodes for Faults at HV Lines

The sag magnitude for all fault types is calculated in relation with the fault distance, which is the distance from the starting point of a particular power line to the fault position. The analytical equations are presented in [7]. A pre-fault voltage of 1 pu and a zero fault impedance are assumed.

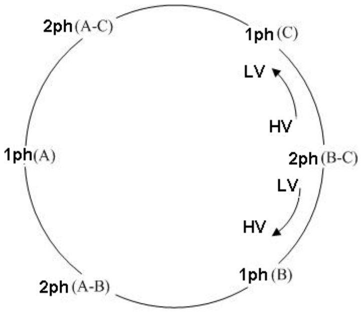


Fig. 2 Sagged phases at the transformer's one side due to faults at the other side. Sagged and faulty phase(s) are in brackets

The sag magnitude of MV nodes (1 to 6) due to faults at HV power lines is the same for all nodes. In Fig. 4, the sag magnitude versus distance to a fault on lines 7-8, 8-9 and 7-9 for each fault type is depicted. 3ph, 2ph and 2ph-g faults on HV side give the same sag magnitude at MV side and 1ph faults give shallow sags, which is due to transformer's vector group.

B. Sag Magnitude of Nodes 1 & 7 for Faults at MV Lines

In Fig. 5 (a), the effect of transformer's phase shift is graphically presented by comparing the sag magnitude of nodes 1 and 7 due to asymmetrical faults on line 7-8 (HV area). It can be seen that in case of 2ph faults (between phases B and C), the Dyn1 transformer results in deterioration as regards the sag magnitude of node 1 with respect to node 7, which is also higher for faults close to node 7. In case of 2ph-g faults (between phases B and C), the situation slightly deteriorates or not at all. In case of 1ph (on phase A) faults, which are the most frequent faults, the situation is significantly improved. It can also be observed that during-fault voltages of phases A and B of node 1 for 2ph, 2ph-g and 3ph faults are equal.

We now consider faults on the LV side and on line 1-4 (Fig. 3) and examine the effect of transformer's phase shift by comparing again the sag magnitude of nodes 1 and 7, as shovn in Fig. 5 (b). In case of 3ph faults, it is not the transformer's phase shift but the transformer's equivalent impedance that affects the sag magnitude. For asymmetrical faults, both of these factors affect the sag magnitude. Again, the during-fault voltage of the most sagged phases (A, C) of node 7 for 1ph faults on LV side is equal. Furthermore, for 2ph and 2ph-g faults, the most sagged phase is phase C.

C. Calculation of Sag Magnitude using Simulations

Apart from short-circuit analysis, simulations can be performed in order to calculate the sag magnitude and to demonstrate the effect of transformer's vector group. In Fig. 8 (Appendix), the sag magnitude of Nodes 1 and 7 (Fig. 3) is calculated through simulations for all fault types on lines 7-8 and 1-2. Faults are applied at the starting (ℓ=0) and the receiving point (ℓ=1) of those power lines but also at the middle of them (ℓ=0.5). In Table II, the results are presented as taken by short-circuit analysis and simulations using PSCAD [19].

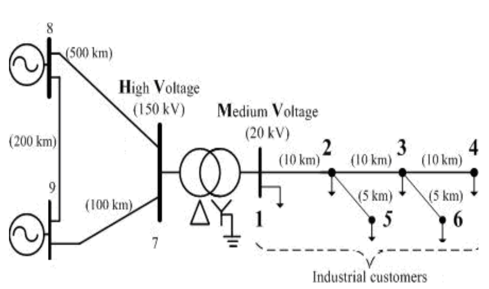


Fig. 3 Single-line diagram of the studied power network

The effect of transformer's vector group on voltage sag characteristics described in Section IV is verified by the simulations. A slight difference on the results taken by simulations is mainly due to the pre-fault voltages, which is difficult to be exactly 1 pu in the simulations as assumed in the short-circuit analysis. Moreover, this difference in the results is due to other small errors and deviations in pu calculations results imported into the simulation parameters. The simulated system including only lines 1-2 of the distribution system and data for results' verification are given in the Appendix.

TABLE II
RESULTS FROM SIMULATIONS AND SHORT-CIRCUIT ANALYSIS

Line	Flt type	ℓ (pu)	Sh. circuit Analysis	PSCAD	Sh. circuit Analysis	PSCAD
			Node 7	Node 7	Node 1	Node 1
7-8	3ph	0	0	0	0	0
		0.5	0.703	0.709	0.703	0.710
		1	0.804	0.822	0.804	0.822
	2ph	0	0.5	0.502	0	0
		0.5	0.789	0.793	0.703	0.710
		1	0.861	0.869	0.804	0.822
	2ph-g	0	0	0	0	0
		0.5	0.705	0.710	0.703	0.710
		1	0.806	0.822	0.804	0.822
	1ph-g	0	0	0	0.816	0.818
		0.5	0.711	0.712	0.944	0.949
		1	0.807	0.825	0.87	0.916
1-2	3ph	0	0.723	0.757	0	0
		0.5	0.853	0.874	0.507	0.520
		1	0.903	0.918	0.677	0.689
	2ph	0	0.723	0.757	0.5	0.501
		0.5	0.853	0.874	0.582	0.590
		1	0.903	0.918	0.708	0.717
	2ph-g	0	0.723	0.757	0	0
		0.5	0.853	0.874	0.53	0.539
		1	0.903	0.918	0.685	0.695
	1ph-g	0	0.871	0.854	0	0
		0.5	0.948	0.957	0.676	0.684
		1	0.968	0.975	0.807	0.814

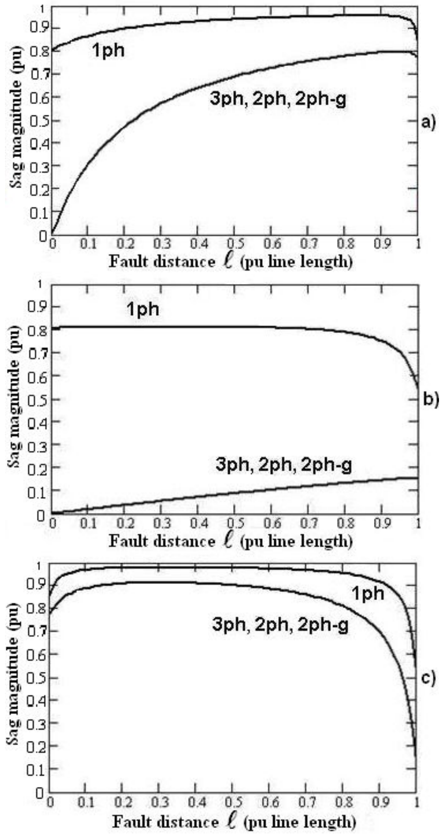


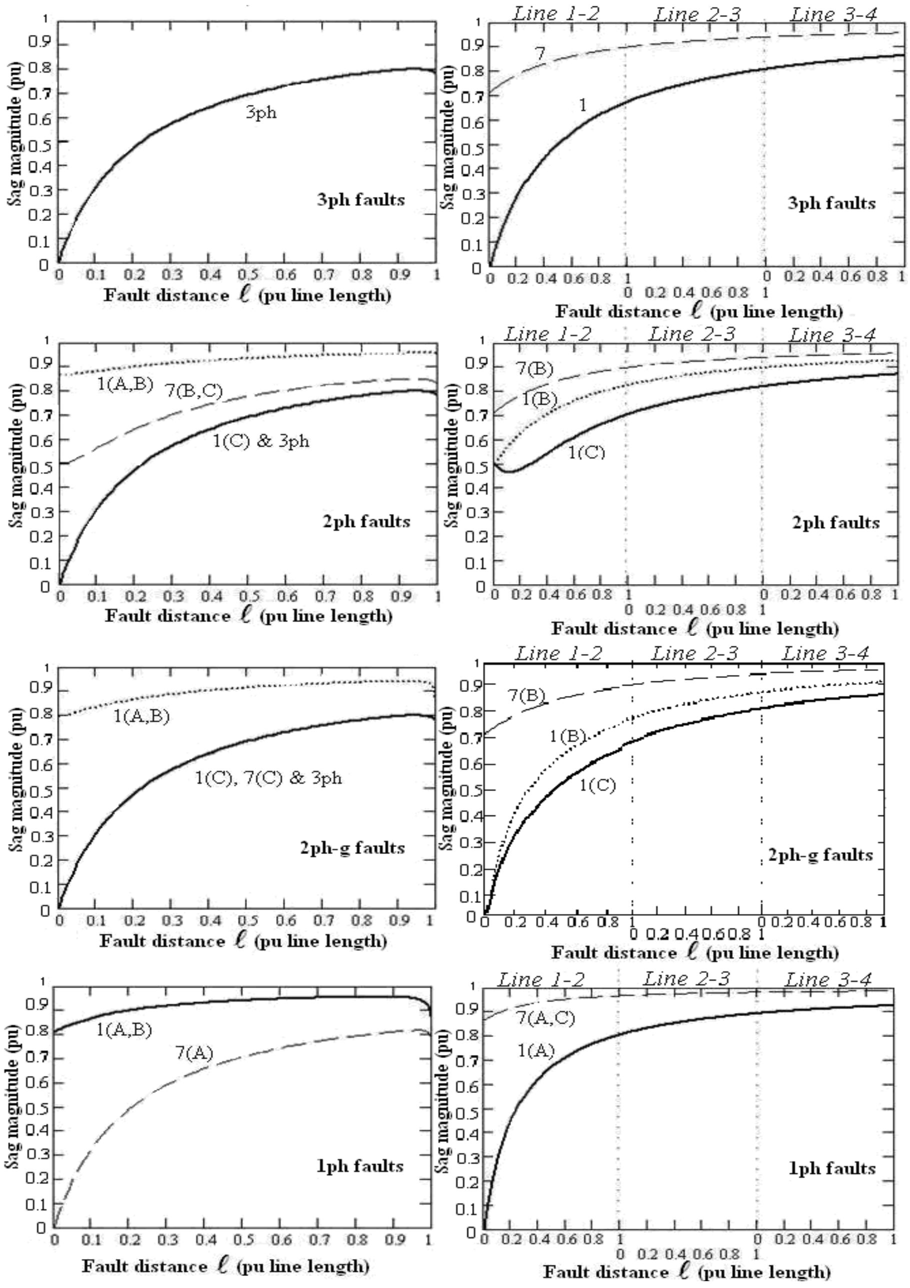
Fig. 4 Sag magnitude of nodes 1 to 6 versus fault (a) Faults on line 7-8 (b) Faults on line 7-9 (c) Faults on line 8-9

VI. STOCHASTIC ASSESSMENT OF SAG FREQUENCY

The effect of transformer's vector group on mitigation of 1ph faults is also reflected on the expected number of sags per year (sag frequency). An attempt is made to quantify this effect on the sag frequency by comparing the results for Nodes 1 and 7 at both sides of the transformer (Fig. 3). The Method of Critical Distances [9] is used, which combines the results taken by short-circuit analysis with stochastic data regarding the probabilities of each fault type (Fig. 6) and fault rates (Table III).

TABLE III
FAULT RATE AT EACH VOLTAGE LEVEL

Voltage level	Fault rate (events/km/year)	Total length (km)
MV (20 kV)	1	40
HV (150 kV)	0.1	800



(a) (b)

Fig. 5 Sag magnitude (solid line) of nodes 7 and 1 for all fault types on: (a) Line 7-8 and (b) line 1-4. In brackets are the sagged phases

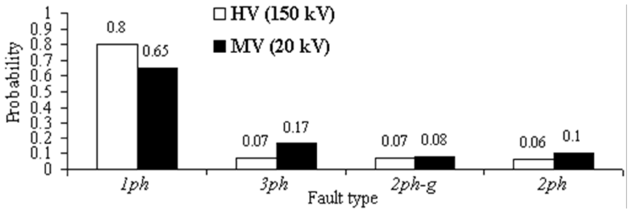
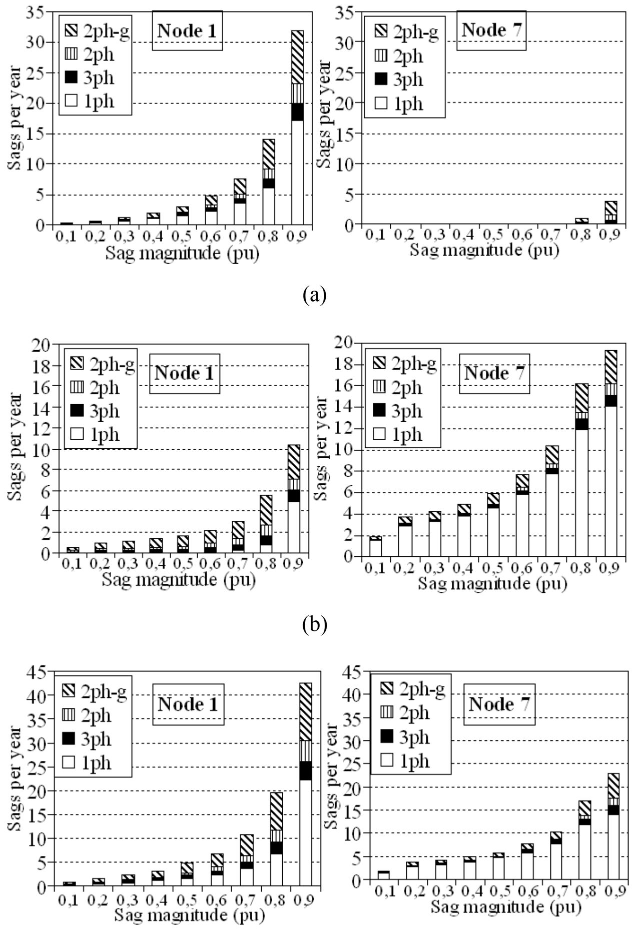


Fig. 6 Probability for each fault type and voltage level

The results for the sag frequency are shown in Fig. 7. In Fig. 7 (a), a 90% reduction in the sag frequency of Node 1 in relation with that of Node 7 when MV is the faulty area can be observed. A 50% reduction in sag frequency is achieved for faults on the HV area. Moreover, the significant contribution of 1ph faults on the sag frequency, despite their mitigation by the transformer, can be observed.



(a)

(b)

(c)

Fig. 7 Cumulative sag frequency of nodes 1 and 7 (a) Faults on MV area (b) Faults on HV area (c) Faults on MV & HV area

VII. CONCLUSION

In this paper, the effect of transformer's vector group on the during-fault voltage characteristics, sag magnitude and frequency is studied. This effect can be validated through analytical equations taken by short-circuit theory or by simulations. The current work focuses on certain transformers, especially them of vector group with a number of 1, 5, 7 and 11.

The main effects of those transformers are:

1) The sag magnitude at the one transformer's side is the same for 3ph, 2ph and 2ph-g faults at the other side under common assumptions used in short-circuit analysis. This means that the sag magnitude is almost equal in real systems. Moreover, only 1ph and 3ph faults can be considered in sag magnitude calculation and frequency assessment studies.
2) Sags due to 1ph faults are significantly mitigated when such a transformer is connected between the faulted area and the examined node or terminal of a load e.g. an industrial customer.
3) Sags due to 2ph faults on the transformer's side firstly met on the fault current flow give more severe 1ph sags to the other side.
4) 1ph sags on the one side is seen as 2ph sags on the other side of the transformer and vice versa.
5) Sag frequency is significantly reduced due to the mitigation of 1ph faults which are far more frequent than the other fault types.

APPENDIX

A. Data Used in the Short-Circuit Analysis

Transformer impedance equals to j0.4 pu. Positive and zero sequence impedance of the two equivalent sources (Fig. 3) are j0.02 pu (Bus 8) and j0.005 pu (Bus 9). Base power equals to 100 MVA. The line impedances are given in Table IV.

B. Data Used in the Simulations

Sources 1 and 2 are selected to be of inductive type with inductances 0.01432 H and 0.00358 H respectively. Star point is grounded and Line-Line voltage (signal parameters) of 150 kV. The positive and zero sequence of power lines (Coupled PI Section Module) are calculated in ohm/m (R, XI, Xc Data) by the values given in Table IV. For the positive and zero capacitance, default values given by PSCAD are used. Value for the line length is taken by Fig. 3. The positive sequence leakage reactance of the transformer with 50MVA nominal power is 0.2 pu and the delta leads the star winding. An ideal transformer is used and default values given by PSCAD are used for the other parameters.

TABLE IV
TRANSMISSION AND DISTRIBUTION LINE IMPEDANCES

Lines	Positive and negative sequence impedance (ohm/km)	Zero sequence impedance (ohm/km)
1-2, 2-3, 3-4	0.22 + j0.37	0.37 + j1.56
2-5, 3-6	1.26 + j0.42	1.37 + j1.67
7-8, 8-9, 7-9	0.097 + j0.391	0.497 + j2.349

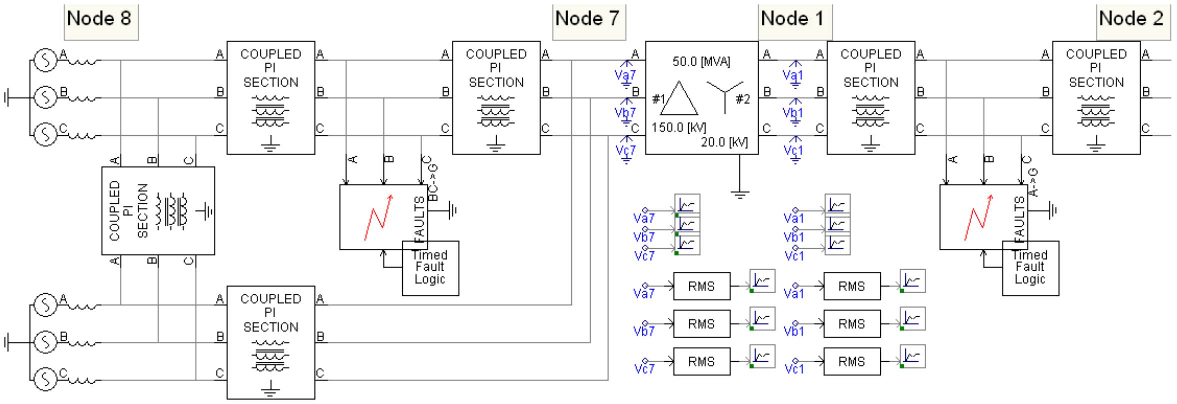


Fig. 8 Studied power network in simulations using PSCAD

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