# The Influence of Transformer Winding Connections on the Propagation of Voltage Sags

Myo Thu Aung, *Student Member, IEEE,* and Jovica V. Milanović, *Senior Member, IEEE*

***Abstract*—This paper presents the influence of different types of transformer winding connections on the propagation of voltage sags caused by symmetrical and asymmetrical faults in the power system. Single and multiple transformers are considered. A particular propagation of voltage sags from customer buses to industry facilities through the transformers employed at the entrance of the facilities is highlighted in the study. Different winding connections, dominantly used in the U.K. distribution networks, were modeled at the service transformers. The study was performed on a generic distribution network, and a bus from the 11-kV distribution network was randomly selected. It was found that the performance of voltage sags inside the industry facility is a function of transformer connections used at the service transformer.**

***Index Terms*—Power quality, propagation of voltage sags, transformer winding connections, voltage sags.**

## NOMENCLATURE

| | |
|---|---|
| $PP$ | Primary side of the transformer self admittance. |
| $PS$ | Primary to secondary mutual admittance. |
| $SS$ | Secondary side of the transformer self admittance. |
| $SP$ | Secondary to primary mutual admittance. |
| $P$ | Primary side of the transformer. |
| $S$ | Secondary side of transformer. |
| $0, 1, 2$ | Zero, positive and negative-sequence quantity, respectively. |
| $Y$ | The transformer admittance in (p.u.) |
| $e$ | $-1\angle 30$. |
| $f$ | $-1\angle -30$. |

## I. INTRODUCTION

IN RECENT years, serious concerns over power quality issues related to voltage sags have been raised by utilities and customers due to the intensive use of sensitive electronic equipment in process automation. When the magnitude and duration of voltage sags exceed the sensitivity threshold of the equipment in the customer's plant, the equipment may fail to operate, thus causing a stop in production with noticeable associated costs [1]. Hence, it is necessary to understand the voltage sags and their characteristics at the equipment's terminals.

The voltage sags are mainly caused by symmetrical or asymmetrical faults in the transmission or distribution systems. A large number of customer buses may experience the voltage sags when the faults occur in the transmission systems. Even through some of these buses are even electrically far away from the original fault locations, they still see the voltage sags as the transmission systems which are dominantly meshed networks and are delivering the bulk power at the higher voltage level. The faults in the distribution systems normally cause the voltage sags at the local customer buses only [2]–[4].

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M. T. Aung is with MottMacDonald, Glasgow G2 8JB, U.K.

J. V. Milanović with the School of Electrical and Electronic Engineering, University of Manchester, Manchester, M60 1QD U.K. (e-mail: milanovic@manchester.ac.uk).

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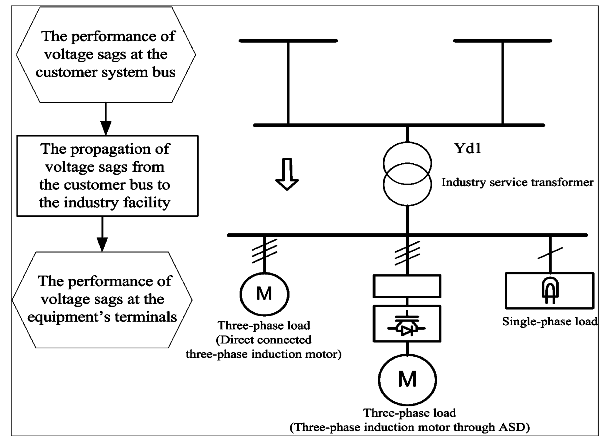



Fig. 1. Propagation of voltage sags from the customer bus to the equipment's terminals.

The number and characteristics of voltage sags known as the performance of voltage sags at the customer buses may differ from each other and from that at the original fault locations. The difference in voltage sags performance i.e., the magnitude and phase angle relationships in particular, is a result of the propagation of voltage sags from the original fault locations to the different customer buses. The propagation of voltage sags through different types of transformer connections results in a different performance of voltage sags on the secondary side of the transformers. Normally, the propagation is referred to as the flow of the voltage sags from the higher voltage to the lower voltage level. Owing to the impedance of the step-down transformers, the reverse direction of the propagation is not significant.

The performance of voltage sags at the customer buses can be assessed by either monitoring or a stochastic approach. The performance at the equipment's terminals however, may alter again from that at the customer buses due to the winding connections of the service transformer employed at the entrance of the industry facility. Hence, a particular propagation of voltage sags from customer buses to the industry facility, as shown in Fig. 1, through different types of service transformer connections needs to be studied. This study is presented in the paper. Initially, the study highlights the characteristics of voltage sags

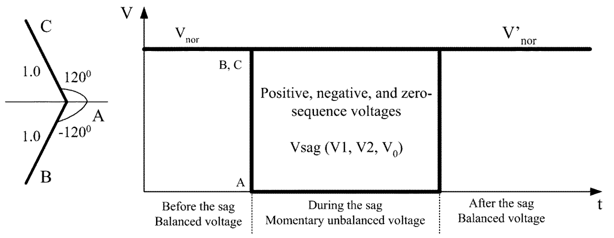



Fig. 2. Magnitude and phase angle relationships of an unbalanced sag caused by a single line-to-ground fault.

and transformer connections and then moves to the influence of each individual transformer connection on the propagation of voltage sags. Finally, intensive analysis of the performance of voltage sags at the equipment's terminals is carried out and the results are discussed.

## II. Characteristics of Voltage Sags

Voltage sags are defined as a decrease in the root-mean-square (rms) value of an ac voltage between 0.1 p.u. and 0.9 p.u. at power frequency for a duration from 0.5 cycles to 1 min [5]–[8]. The duration of voltage sags is described as the total time interval between the point on wave of sag initiation and recovery [6], [9]. The magnitude and the duration of voltages sag in use in this paper are the remaining bus voltage during the fault and the required time to clear the fault by primary protection, respectively. Magnitude and duration are the main characteristics of voltage sags, and they have been used for the development of the equipment's compatibility charts and indices. In addition to these, the other characteristics such as unbalanced voltage sags, phase angle shifts, the point on the wave of initiation and recovery, and waveform distortion have been found to influence significantly the equipment's sensitivity to the voltage sags [1].

The majority of faults in the power systems are the single line-to-ground faults [2], and consequently result in the unbalanced voltage sags, as shown in Fig. 2. All sequence quantities: Positive, negative, and zero sequence, are involved in such kind of sags. Similarly, the voltage sags caused by the double line-to-ground faults also contain all sequence quantities. However, the sags due to the three-phase symmetrical faults consist of only positive sequence-quantities whereas the progress of positive and negative sequence quantities in the voltage sags are due to the occurrence of the line-to-line faults. As a result of that, voltage sags caused by asymmetrical faults can be described as the momentary unbalanced sags.

## III. Effects of Transformer Connections on the Propagation of Sags

The influence of transformer winding connections on the propagation of voltage sags, as shown in Fig. 3, can be seen when these sags contain zero-sequence quantities and the transformer connections do not allow the flow of those sequence quantities. In some voltage sags, zero-sequence quantities are not involved, though the influence can still be expected for the reason of the transformers themselves introducing a phase shift. Also, the influence occurs because of the combination of the former. Therefore, as shown in Fig. 4, the transformer connections can be categorized into three main groups according to their effects on the propagation of sags.

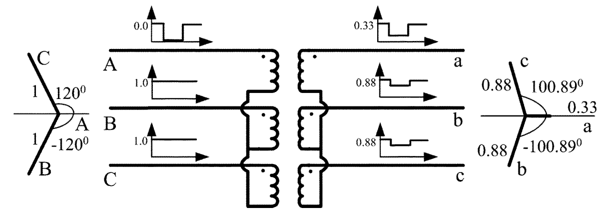



Fig. 3. Propagation of a voltage sag caused by a single line-to-ground fault passing through a Yy0 transformer.

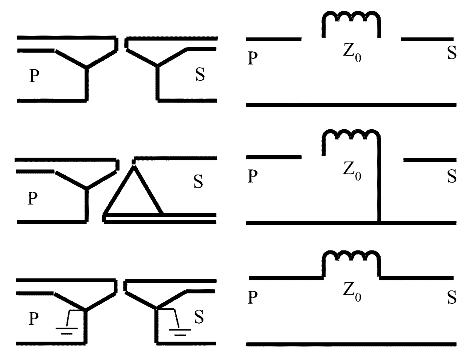



Fig. 4. Zero-sequence equivalent circuits of the corresponding transformer winding connections.

The difference in the performance of voltage sags between the primary and secondary sides of the transformers appears when the voltage sags caused by single line-to-ground or double line-to-ground faults pass through the Yy0 or Dd0 [1]transformers because, as shown in Fig. 4, these transformers prevent the flow of zero-sequence quantities [10]. The similar sags can, however, be seen on the secondary side of the Yy0 or Dd0 transformers if these sags are caused by the line-to-line faults. For example, as shown in Table I, a voltage sag caused by the single line-to-ground or double line-to-ground fault (a sag in one phase or two phases) turns into a sag with different magnitude and phase angle relationships (a sag in all three phases) when it flows through the Yy0 or Dd0 transformers. On the other hand, these transformers help to maintain the voltage sag magnitude on the secondary side above 0.33 p.u., even if a voltage sag with zero magnitude, i.e., a momentary interruption, appears on the primary side. As a consequence, the interruptions are never experienced on the secondary side of the Yy0 or Dd0 transformers due to the asymmetrical faults. The Yyg or YGy transformers have the same effect on voltage sags as the previously mentioned Yy0 or Dd0 transformers.

The difference becomes significant when the voltage sags propagate through the Yd1 transformers as such transformers resist the transfer of zero-sequence quantities like the Yy0 or

[1]The symbols used for describing types of transformer winding connections are the following: the capital letter "Y" or the small letter "y" stands for wye winding connection while the letter "D" or "d" refers to delta connected windings. Capital letters represent the primary side of transformer whereas the secondary side is denoted by small letters. The numbers, i.e., 0, 1, 2, 3–11, indicate phasor relationships between primary and secondary connections [12],[13].

TABLE I
PROPAGATION OF A VOLTAGE SAG CAUSED BY EACH ASYMMETRICAL FAULT THROUGH THE YY, YYG, YGY, OR DD TRANSFORMER

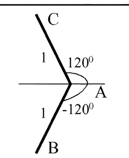
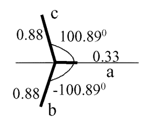
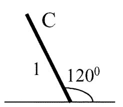
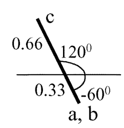
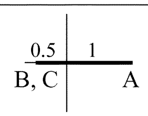
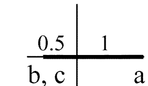
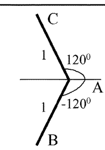
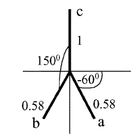
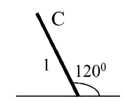
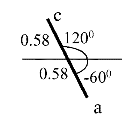
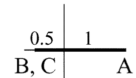
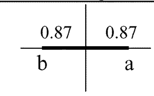
| A voltage sag caused by | Transformer connection | The propagated voltage sag |
|---|---|---|
|  A single line-to-ground fault | Yy0<br>Yygo<br>YGy0<br>Dd0 |  A sag in all three phases |
|  A double line-to-ground fault | Yy0<br>Yygo<br>YGy0<br>Ddo |  A sag in all three phases |
|  A line-to-line fault | Yy0<br>Yygo<br>YGy0<br>Ddo |  An identical sag |

TABLE II
PROPAGATION OF A VOLTAGE SAG CAUSED BY EACH ASYMMETRICAL FAULT THROUGH THE YD, DY, YGD, OR DYG TRANSFORMER

| A voltage sag caused by | Transformer connection | The propagated voltage sag |
|---|---|---|
|  A single line-to-ground fault | Dy1<br>Yd1<br>YGd1<br>Dyg1 |  A sag in two phases |
|  A double line-to-ground fault | Dy1<br>Yd1<br>YGd1<br>Dyg1 |  A sag in two phases and an interruption on the other phase |
|  A line-to-line fault | Dy1<br>Yd1<br>YGd1<br>Dyg1 |  A sag in two phases and an interruption on the other phase |

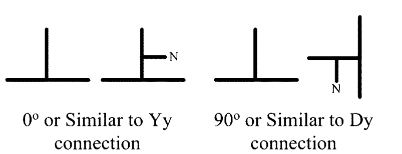
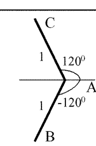
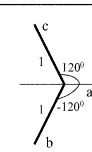
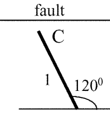
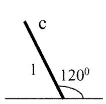
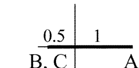
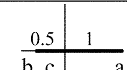



Fig. 5. Orientation of windings in T connection.

TABLE III
PROPAGATION OF A VOLTAGE SAG CAUSED BY EACH ASYMMETRICAL FAULT THROUGH THE YGYG0 TRANSFORMER

| A voltage sag caused by | Transformer connection | The propagated voltage sag |
|---|---|---|
|  A single line-to-ground fault | YGyg0 |  An identical sag |
|  A double line-to-ground fault | YGyg0 |  An identical sag |
|  A line-to-line fault | YGyg0 |  An identical sag |

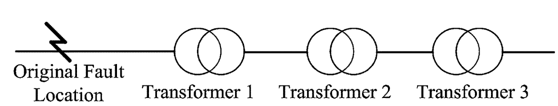



Fig. 6. Transformers in cascade.

Dd0 transformers; in addition to this, phase shifts also appear on the secondary side of these transformers, as shown in Fig. 4.

The degree of the phase shifts depend on the way that phases are labeled, it may be $\pm 30°$, $\pm 90°$ or $\pm 150°$ for the Yd transformers [11], [12]. The phase shifts can also be expected in the T-T transformers, as shown in Fig. 5, depending on the orientation of their primary and secondary winding [13].

The Yd1 transformers yield other characteristics of voltage sags (a sag in two phases and the other phase may be healthy or may see an interruption). As shown in Table II, similar to the Yy0 or Dd0 transformers, the voltage sag magnitude in two phases of the secondary side of the Yd transformers will not be less than 0.58 p.u. In contrast, the other phase may be perfectly healthy in the case of the propagation of the voltage sags caused by the single line-to-ground faults. For any other asymmetrical faults, an interruption may be seen. As a result of that, phase angle asymmetry on the secondary side of the Yd1 transformers is relatively higher than that on the secondary side of the Yy or Dd transformers. As shown in Table II, the Dy, Dyg, and YGd transformers also behave in a similar way to Yd1 transformers.

As shown in Table III, the propagation of voltage sags caused by all types of asymmetrical faults through the YGyg transformers results in the identical voltage sags on the secondary side as these transformers, as shown in Fig. 4, permit all sequence components to pass through.

As far as the propagation of voltage sags caused by three-phase symmetrical faults is concerned, the changes in voltage sag performance appear only on the secondary side of the Yd transformers.

In relation to the propagation of voltage sags through the multiple Yy transformers, as shown in Fig. 6, only the first Yy transformer will change the characteristics of voltage sags on its secondary side. The following transformers will, however, yield the identical voltage sags, as shown in Table IV, since zero-sequence quantities have been removed by the first transformer.

TABLE IV
THE PROPAGATION OF A VOLTAGE SAG THROUGH THE MULTIPLE YY TRANSFORMERS

| Voltage Sag Caused by | Voltage Sag at the Original Fault Location | After Propagation through the First Yy Transformer | After Propagation through the Second Yy Transformer | After Propagation through the Third Yy Transformer |
|---|---|---|---|---|
| Single Line-to-Ground Fault | C 1 120° A 1 -120° B | c 0.88 100.89° 0.33 a 0.88 -100.89° b | c 0.88 100.89° 0.33 a 0.88 -100.89° b | c 0.88 100.89° 0.33 a 0.88 -100.89° b |
| Double Line-to-Ground Fault | C 1 120° | c 0.66 120° 0.33 -60° a, b | c 0.66 120° 0.33 -60° a, b | c 0.66 120° 0.33 -60° a, b |
| Line-to-Line Fault | 0.5 1 B, C A | 0.5 1 b, c a | 0.5 1 b, c a | 0.5 1 b, c a |

TABLE V
PROPAGATION OF A VOLTAGE SAG THROUGH THE MULTIPLE YD TRANSFORMERS

| Voltage Sag Caused by | Voltage Sag at the Original Fault Location | After Propagation through the First Yd Transformer | After Propagation through the Second Yd Transformer | After Propagation through the Third Yd Transformer |
|---|---|---|---|---|
| Single Line-to-Ground Fault | C 1 120° A 1 -120° B | c 1 150° 60° 0.58 b 0.58 a | 0.88 c 0.33 79.11° b -79.11° 0.88 a | b c 0.58 0.58 60° 150° 1 a |
| Double Line-to-Ground Fault | C 1 120° | c 0.58 120° 0.58 -60° a | b, c 0.33 120° -60° 0.66 a | b 0.58 120° 0.58 -60° a |
| Line-to-Line Fault | 0.5 1 B, C A | 0.87 0.87 b a | 1 0.5 b a, c | 0.87 0.87 b c |

When the Yd transformers are in cascade, every odd or even transformer will produce the similar characteristics of voltage sags, as shown in Table V. These two characteristics however, are different. The sag characteristics on the secondary of the even transformers are similar to the ones given by the Yy transformers. Also, these characteristics are close to the ones at the original fault locations in the case of the propagation of voltage sags caused by the line-to-line faults. The characteristics of voltage sags are similar, though the phase angle orientation and the phases involved are different. The odd transformers, on the other hand, still result in the interruptions on their secondary sides apart from the case of the propagation of voltage sags caused by the single line-to-ground faults.

Turning to the connection in which the Yy and Yd transformers are together in series, the effects of the Yy transformers on the propagation of voltage sags are highly dependent on their locations. As shown in Tables VI and VII, the effects can only be expected when the Yy transformers are ahead of their counterparts. Regardless of the locations, the Yd transformers will keep changing the characteristics of voltage sags as a result of the introduction of the phase shifts.

## IV. STUDY METHODOLOGY

The methodology that was used in this paper is based on the guidelines of IEEE Std C57.105-1978 and transformer modeling by [12]. The relation between voltages and currents on the primary and secondary sides of a three-phase transformer can be expressed by using its admittance matrix

$$\begin{bmatrix} I_P \\ I_S \end{bmatrix} = Y \begin{bmatrix} V_P \\ V_S \end{bmatrix}. \tag{1}$$

The admittance matrix of the transformer is stated in (2). Elements of the matrix are dependent on the winding connections considered.

$$Y = \begin{bmatrix} Y_{\mathrm{PP}} & Y_{\mathrm{PS}} \\ Y_{\mathrm{SP}} & Y_{\mathrm{SS}} \end{bmatrix}. \tag{2}$$

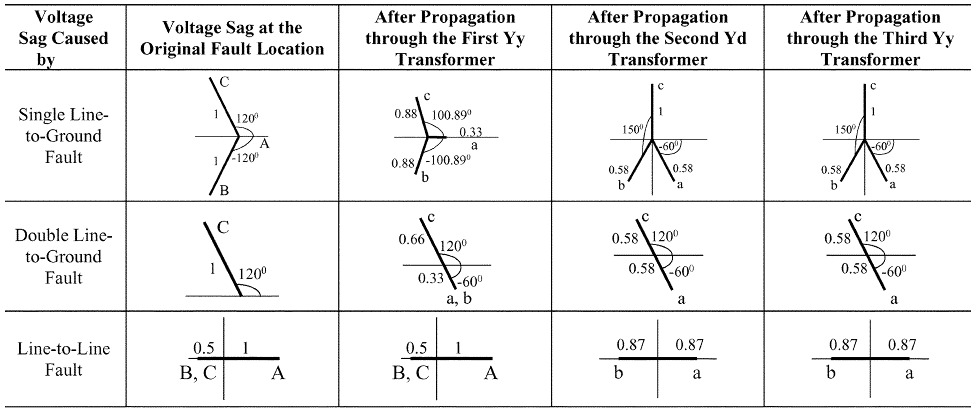
The admittance matrix can be converted into the sequence quantities, as given in (3)

$$Y_{012} = A^{-1} Y A \tag{3}$$

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \tag{4}$$

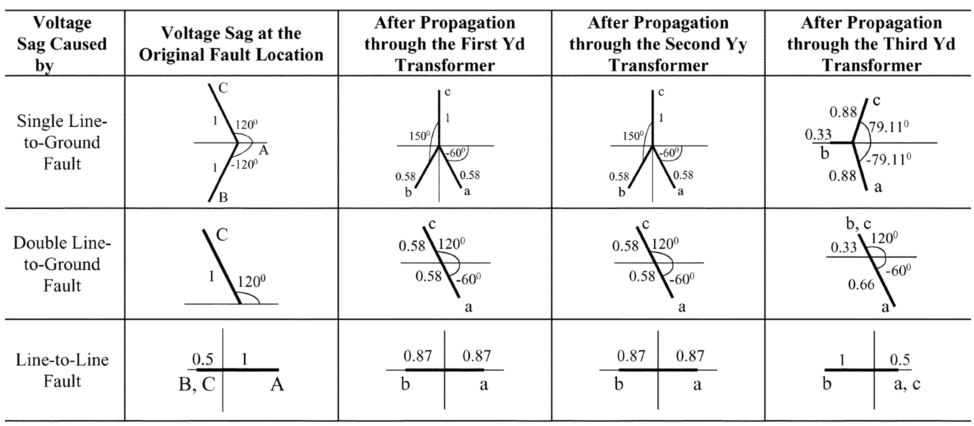
$$A^{-1} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}. \tag{5}$$

TABLE VI
PROPAGATION OF A VOLTAGE SAG THROUGH THE SERIES CONNECTION OF YY AND YD TRANSFORMERS-1



| Voltage Sag Caused by | Voltage Sag at the Original Fault Location | After Propagation through the First Yy Transformer | After Propagation through the Second Yd Transformer | After Propagation through the Third Yy Transformer |
|---|---|---|---|---|
| Single Line-to-Ground Fault | C; 1; 120°; A; 1; -120°; B | c; 0.88; 100.89°; 0.33; a; 0.88; -100.89°; b | c; 1; 150°; -60°; 0.58; b; 0.58; a | c; 1; 150°; -60°; 0.58; b; 0.58; a |
| Double Line-to-Ground Fault | C; 1; 120° | c; 0.66; 120°; 0.33; -60°; a, b | c; 0.58; 120°; 0.58; -60°; a | c; 0.58; 120°; 0.58; -60°; a |
| Line-to-Line Fault | 0.5; 1; B, C; A | 0.5; 1; B, C; A | 0.87; 0.87; b; a | 0.87; 0.87; b; a |

TABLE VII
PROPAGATION OF A VOLTAGE SAG THROUGH THE SERIES CONNECTION OF YY AND YD TRANSFORMERS-2



| Voltage Sag Caused by | Voltage Sag at the Original Fault Location | After Propagation through the First Yd Transformer | After Propagation through the Second Yy Transformer | After Propagation through the Third Yd Transformer |
|---|---|---|---|---|
| Single Line-to-Ground Fault | C; 1; 120°; A; 1; -120°; B | c; 1; 150°; -60°; 0.58; b; 0.58; a | c; 1; 150°; -60°; 0.58; b; 0.58; a | c; 0.88; 79.11°; 0.33; b; -79.11°; 0.88; a |
| Double Line-to-Ground Fault | C; 1; 120° | c; 0.58; 120°; 0.58; -60°; a | c; 0.58; 120°; 0.58; -60°; a | b, c; 0.33; 120°; -60°; 0.66; a |
| Line-to-Line Fault | 0.5; 1; B, C; A | 0.87; 0.87; b; a | 0.87; 0.87; b; a | 1; 0.5; b; a, c |

As shown in (6), sequence voltages and currents on the primary and secondary sides of the three-phase transformer can be obtained

$$\begin{bmatrix} I_{P012} \\ I_{S012} \end{bmatrix} = Y_{012} \begin{bmatrix} V_{P012} \\ V_{S012} \end{bmatrix}. \tag{6}$$

For example purposes, the admittance matrix of the Yd1 transformer is stated in (7) and its vector diagram is illustrated in Fig. 7. By performing the matrix operation, the sequence voltages on the secondary side of the Yd1 transformation can be calculated. Throughout the calculation, the load current under the faulted condition and the transformer impedance are taken into account

$$\begin{bmatrix} I_{P0} \\ I_{P1} \\ I_{P2} \\ I_{S0} \\ I_{S1} \\ I_{S2} \end{bmatrix} = y \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & e & 0 \\ 0 & 0 & 1 & 0 & 0 & f \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & f & 0 & 0 & 1 & 0 \\ 0 & 0 & e & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} V_{P0} \\ V_{P1} \\ V_{P2} \\ V_{S0} \\ V_{S1} \\ V_{S2} \end{bmatrix}. \tag{7}$$

## V. STUDY NETWORK

A generic distribution system (GDS) is used as a study network. It consists of a 230-kV transmission system in feed, a 33-kV subtransmission network, and an 11-kV predominantly meshed distribution network. Some parts of the distribution network however are, radial. The GDS is formed by 295 buses and 296 overhead lines and underground cables. Furthermore, different types of transformer winding connections, such as YGyg, Yy, YGy, and Yd, are modeled in the network.

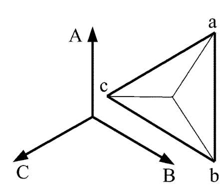



Fig. 7. Vector diagram of the Yd1 transformer.

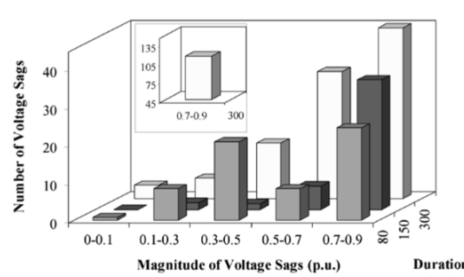



Fig. 8. Performance of voltage sags with respect to the magnitude and duration at the customer bus.

Symmetrical and asymmetrical faults were simulated on the network in each phase separately and at each fault position using commercially available software SIMPOW [14]. Each fault position represented a single fault at the system bus or at the particular fault location along each line. Details of the description of the fault position model and the typical fault clearing time used in the paper are given in [15].

## VI. Study Procedure

In order to investigate the influence of transformer winding connections on the propagation of voltage sags, the following procedure was used. The load flow study was performed and realistic prefault voltages and load currents were recorded.

1) The system wide fault analysis was performed (stochastic voltage sag analysis based on fault position method [1], [15]), and voltages and load currents during the fault were recorded.
2) A voltage sag database was created by importing system fault analysis data associated with corresponding fault locations and fault rates, and typical fault clearing time determined by the reaction of primary protection.
3) A customer site, bus 89, from the 11-kV solidly grounded distribution system was arbitrarily selected as a bus of interest.
4) Sequence voltages during the fault on the secondary side of the service transformers (the industry facility side) were calculated by performing the matrix operation.
5) The sequence quantities were converted into phase quantities (complex voltages).
6) Finally, the number and characteristics of voltage sags inside the industry facility was determined.

## VII. Case Studies

In order to highlight the influence of transformer winding connections on the propagation of voltage sags, the following transformer winding connections are modeled at the service transformer to the industry facility. These connections are dominantly used in the UK distribution system: 1) Yy0 transformer; 2) Dd0 transformer; 3) YGyg transformer; 4) Yd1 transformer (ANSI Standard); 5) Yd11 transformer, and 6) Yd5 transformer.

## VIII. Results of the Analysis

The influence of the transformer winding connections on the propagation of voltage sags is illustrated in Figs. 8–16. The influence on the performance of voltage sags with respect to the magnitude and the phase shifts is demonstrated in Figs. 9–11 and Figs. 13–16, respectively. The performance of voltage sags at the customer bus is given in Figs. 8 and 12. The figures indicate that depending on the transformer winding connections, different performance of voltage sags at the equipment's terminals can be expected. The differences may vary from a small number to a large number of voltage sags.

(*Note:* Due to the much higher number of sags in certain voltage ranges, the top parts of the corresponding columns in Figs. 8 to 16 are presented as the inserts in order to show clearly the difference in the number of voltage sags and to preserve uniformity of the representation.)

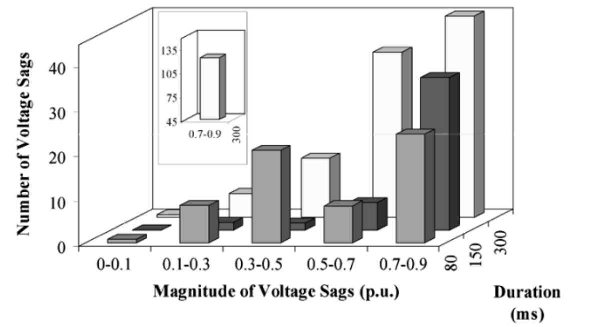



Fig. 9. Performance of voltage sags with respect to the magnitude and duration at the secondary side of the Yy0 or Dd0 transformer.

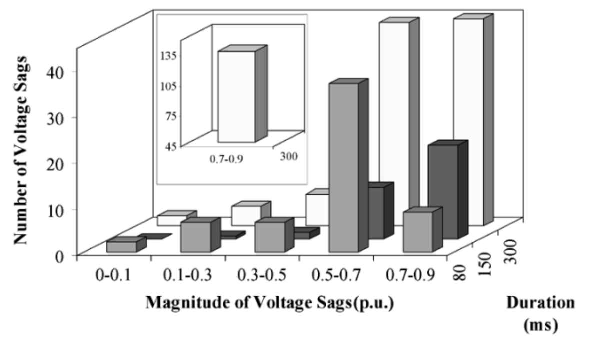



Fig. 10. Performance of voltage sags with respect to the magnitude and duration at the secondary side of the Yd1, Yd11 or Yd5 transformers.

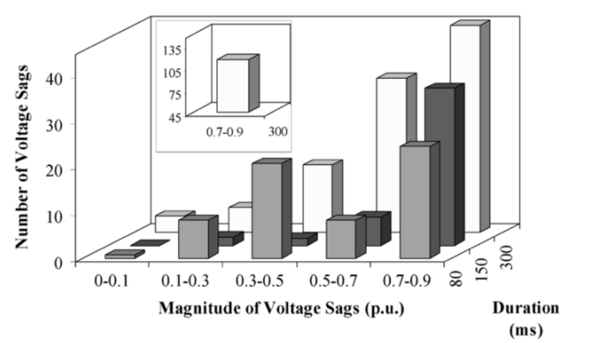



Fig. 11. Performance of voltage sags with respect to the magnitude and duration at the secondary side of the YGyg transformer.

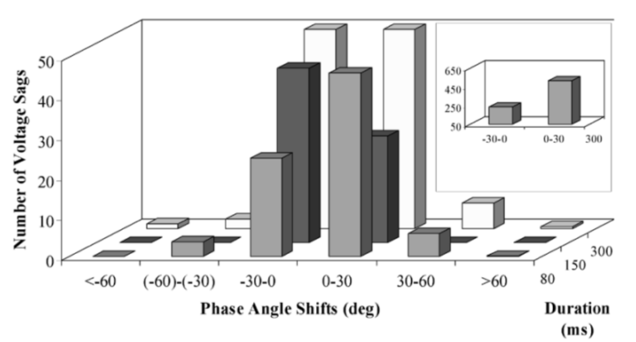



Fig. 12. Performance of voltage sags with respect to the phase shifts and duration at the customer bus.

As shown in Fig. 9, compared to the performance of voltage sags at the customer bus (Fig. 8), an 80% decrease in the

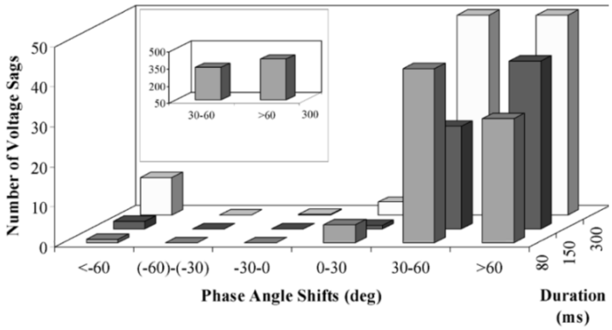



Fig. 13. Performance of voltage sags with respect to the phase shifts and duration at the secondary side of the Yd1 transformer.

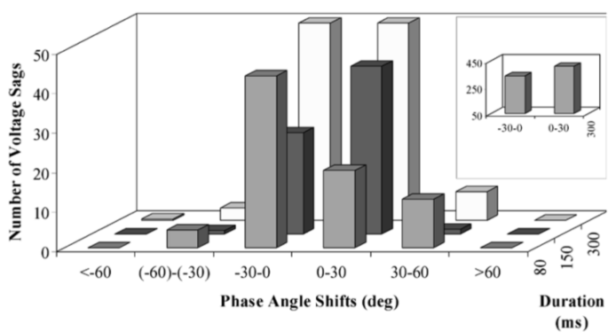



Fig. 14. Performance of voltage sags with respect to the phase shifts and duration at the secondary side of the Yd11 transformer.

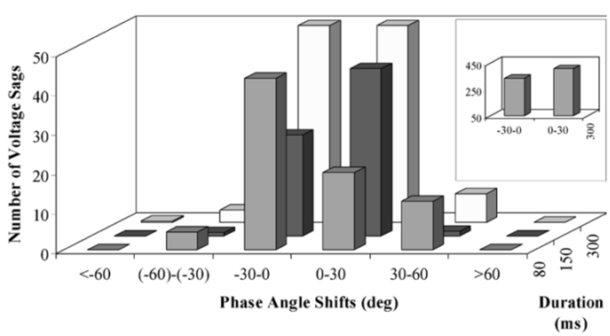



Fig. 15. Performance of voltage sags with respect to the phase shifts and duration at the secondary side of the Yd5 transformer.

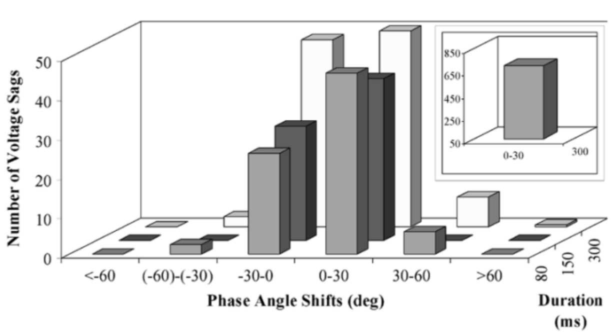



Fig. 16. Performance of voltage sags with respect to the phase shifts and duration at the secondary side of the Yy0 or Dd0 transformer.

number of momentary interruptions having the duration of 300 ms occurs due to the use of the Yy0 or Dd0 winding connections. Also, a small variation can be seen in the other magnitude ranges.

As demonstrated in Fig. 10, a reduction in the severe voltage sags with the magnitude less than 0.5 p.u. appears in the application of the Yd1, Yd11 or Yd5 transformer. The reduction ranges considerably from 8% to 69%. The significant reduction occurs when the voltage sags are in the range of 0.3–0.5 p.u. and 80 ms. An increase in the range from 24% to 77% however, can be seen in the case of the medium voltage sags, which have the magnitude of 0.5–0.7 p.u. The increase in the number of voltage sags with the duration of 80 ms is particularly pronounced. Different variation patterns can be observed in the case of shallow voltage sags having the magnitude of 0.7–0.9 p.u. The number of voltage sags with the duration of 300 ms rises by 14%, whereas the number of other voltage sags drops by 64% and 40%, respectively. As far as the momentary interruptions are concerned, the interruptions with the duration of 80 ms are increased by 66%.

Fig. 11 clearly indicates that there is no influence of the Ygyg transformer connections on the propagation of voltage sags since the identical performance of voltage sags appears on the secondary side of the transformers.

As far as the influence on the phase shifts is concerned, it was found that the Yd transformers produce stronger effects than the Yy0 or Dd0 transformers. Fig. 13 indicates that the vast majority of the phase shifts are in the range of 30°–60° and greater than 60° when the Yd1 transformer connections are in use. The Yd11 and Yd5 transformers, however, narrow the phase shifts down to the range of ±30°, as shown in Figs. 14 and 15. It can be seen from Fig. 16 that the phase shifts will be in the range of ±30° when the Yy0 or Dd0 transformers are used.

It should be mentioned that the phase shifts are defined as the difference in phase angle of the voltages before the fault and during the fault. As a result of that, positive phase shifts indicate that the voltages during the fault lag behind the voltages before the fault.

## IX. Conclusion

This paper presented the results of the intensive analysis of the influence of transformer connections on the propagation of voltage sags. It is clearly shown that the influence is highly dependent on the type of the transformer winding connection used.

The Yd transformer winding connection has a stronger influence than any other type of transformer winding connection as these Yd transformers reduce the number of severe voltage sags and increase the number of medium voltage sags. The results however, indicate that a higher number of momentary interruptions can be expected with these types of transformer connections. It can be seen that the Yd1, Yd11, or Yd5 transformers yield the identical magnitude of voltage sags though, the associated phase shifts are completely different from each other. This warrants that the magnitude and the phase shifts together ought to be considered whenever the sensitivity of the equipment to voltage sags needs to be determined.

It was also shown that the Yy0 or Dd0 transformer connections reduce the number of momentary interruptions.

The results indicate the importance of the winding connections used at the service transformer to the industry facility. The characteristics of voltage sags at the equipment's terminals vary according to the winding connections of the service transformer. Direct projection of the performance at the customer bus to the equipment's terminals will result in an erroneous prediction of the equipment's failure or misoperation in the plant. Also, estimation of the cumulative loss in revenue that might result from voltage sags should be based on the performance effect of voltage sags at the equipment terminals.

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**Myo Thu Aung** (S'00) received the B.E. degree in electrical engineering from Yangon Technological University, Rangoon, Burma, the M.E. degree in electric power system management from the Asian Institute of Technology, Bangkok, Thailand, and the Ph.D. degree from the University of Manchester, (formerly UMIST) Manchester, U.K.

He is currently with the Power System Group at MottMacDonald, Glasgow, U.K.

**Jovica V. Milanović** (M'95–SM'98) received the Dipl.Ing. and M.Sc. degrees from the University of Belgrade, Belgrade, Yugoslavia, and the Ph.D. degree from the University of Newcastle, Newcastle, Australia.

He is a Professor with the School of Electrical and Electronic Engineering, The University of Manchester (formerly UMIST), Manchester, U.K., where he has been since 1998.