Power Quality Assessment of Specially Connected Transformers

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Abstract: This paper examines and compares the voltage deviation, voltage unbalance, and harmonic distortion of VqV, Scott, and Le Blanc connected transformers by a novel approach. The power quality factors are needed to truly reflect the loading characteristics of these transformers. The computation results of several loading cases and simulation cases demonstrate the differences. The level of voltage unbalance of the V-V connection scheme is substantially worse than that of the Scott and Le Blanc connection schemes in normal operation. So the voltage deviation, voltage unbalance, and harmonic distortion are important indexes of power quality for these transformers.

Key-Words: power quality, V-V connection, Scott connection, Le Blanc connection.

1 Introduction

The voltage deviation, voltage unbalance, and harmonic distortion are indexes of power quality degradation. Some momentary events cause under-voltage during the transient period until protection relay are activated, and the circuit breaker is used to clear the faults. Possible and inevitable causes of faults in power systems include grounding faults, poor insulation of equipment, or transmission line faults caused by animals or other objects. For example, the power system transmission line is suddenly struck by lightning. When voltage sag occurs, the voltage value fall may to between 10% and 90% of the normal value in a period of 0.5 cycles to a few seconds [1-2]. The drop of voltage sag has been studied determined by the system impedances and fault types [3-6]. The voltage unbalance can lead to current unbalance of other loads. ANSI (American National Standards Institute) and IEC (International Electrotechnical Commission) suggested that generator and electric motor should have limit current unbalance when they are operating.

More and more nonlinear loads have been used in power systems with the development of power electronic technology. However, the nonlinear characteristics generate harmonic currents [7]. The IEEE Standard 519-1992 provides a guideline for the limitation and mitigation of harmonics [8].

Railway electrification system usually required strong single-phase power sources, but the single-phase loads cause voltage deviation and voltage unbalance disturbances to the three-phase sources. Therefore, some specially connected transformers, such as the V-V, Scott, and Le Blanc connection schemes, are utilized in the railway electrification system to reduce the unbalance effect. The increasing study to power quality issues in railway electrification systems today is leading to investigates on the repercussion of traction loads on three-phase power systems. Recent investigates about the specially connected transformers have been steadily on the increase, such as modeling for particular investigates, evaluating voltage unbalance, discussing the effect of harmonics distortion, and revising the differential protection methods. For example, simplified models of specially connected transformers were proposed to study three-phase power flow [9]. A network model has been applied in unbalanced effects studies [10]. A rigorous method to evaluate the voltage unbalance due to specially connected transformers has been proposed [11]. The loading characteristic analysis of specially connected transformers were studied [12].

However, voltage deviation, voltage unbalance and harmonic distortion viewed from the primary side of specially connected transformers should be examined in details. This investigation examines and compares the voltage deviation, voltage unbalance, and harmonic distortion of the V-V, Scott and Le Blanc connected transformers in a novel approach. The analytical results reveal that the V-V connection scheme has more serious unbalanced disturbances in the three-phase sources than the Scott and Le Blanc connection schemes.
2 Circuit Analysis of Transformers

To illustrate the V-V, Scott, and Le Blanc transformer connection, let \( k_1 = \frac{N_1}{N_2} \) and \( k_2 = \frac{N_3}{N_1} \) denote the turn ratios.

A. V-V connection

The V-V connection scheme is composed of two single-phase transformers. The transformer uses three-phase power on the primary side, and supplies two single-phase loads on the secondary side. The voltages and currents relationships are got form Fig. 1 respectively, as follows.

\[
\begin{bmatrix}
    V_T \\
    V_M
\end{bmatrix} = k_1 \begin{bmatrix}
    1 & -1 & 0 \\
    0 & 1 & -1
\end{bmatrix} \begin{bmatrix}
    V_a \\
    V_b \\
    V_c
\end{bmatrix},
\]

(1)

\[
\begin{bmatrix}
    T_a \\
    T_b \\
    T_c
\end{bmatrix} = k_2 \begin{bmatrix}
    1 & 0 \\
    -1 & 1 \\
    0 & -1
\end{bmatrix} \begin{bmatrix}
    T_T \\
    T_M
\end{bmatrix},
\]

(2)

B. Scott connection

Fig. 2 shows the circuit diagram of the Scott connected transformer, which contains two different turn ratio transformers. It also transforms three-phase power to two-phase power. The main Transform (phase M) has a middle-tapped winding on its primary side, and a single winding on its secondary side. The teaser transformer (phase T) is a single-phase transformer. The voltages and currents relationships are, respectively, as follows.

\[
\begin{bmatrix}
    V_T \\
    V_M
\end{bmatrix} = k_1 \begin{bmatrix}
    2/\sqrt{3} & -1/\sqrt{3} & -1/\sqrt{3} \\
    0 & 1 & -1
\end{bmatrix} \begin{bmatrix}
    V_a \\
    V_b \\
    V_c
\end{bmatrix},
\]

(3)

\[
\begin{bmatrix}
    T_a \\
    T_b \\
    T_c
\end{bmatrix} = k_2 \begin{bmatrix}
    2/\sqrt{3} & 0 \\
    -1/\sqrt{3} & 1 \\
    -1/\sqrt{3} & -1
\end{bmatrix} \begin{bmatrix}
    T_T \\
    T_M
\end{bmatrix},
\]

(4)

C. Le Blanc connection

The connection scheme of the Le Blanc transformer is shown in Fig. 3. The primary windings are the same as those of a common three-phase transformer in delta connection. The secondary side consists of five windings, which are separated into two phases. The voltages and currents relationships are, respectively,

\[
\begin{bmatrix}
    V_T \\
    V_M
\end{bmatrix} = k_1 \begin{bmatrix}
    -2/\sqrt{3} & 1/\sqrt{3} & 1/\sqrt{3} \\
    0 & 1 & -1
\end{bmatrix} \begin{bmatrix}
    V_a \\
    V_b \\
    V_c
\end{bmatrix},
\]

(5)

\[
\begin{bmatrix}
    T_a \\
    T_b \\
    T_c
\end{bmatrix} = k_2 \begin{bmatrix}
    -2/\sqrt{3} & 0 \\
    1/\sqrt{3} & 1 \\
    1/\sqrt{3} & -1
\end{bmatrix} \begin{bmatrix}
    T_T \\
    T_M
\end{bmatrix},
\]

(6)

3 Voltage Deviation, Voltage Unbalance, and Harmonic Distortion

A. Voltage deviation (\( \Delta V \))

The voltage deviation is derived when there is a single-phase ground fault or two-phase ground fault on secondary side load bus. Then voltage deviation on the primary side is given by

\[
\Delta V = \frac{\text{ratio voltage} - \text{fault voltage}}{\text{ratio voltage}}
\]

(7)

B. Voltage unbalance (U)

The voltage unbalance values are defined in two categories by the IEC Standard 61000. There are

\[
U_R = \frac{\text{Max. deviation from Vavg}}{\text{Vavg}}
\]

(8)

\[
U_{Sd0} = \frac{\text{zero - sequence voltage}}{\text{positive - sequence voltage}} = \frac{V_0}{V_1}
\]

(9)

\[
U_{Sd2} = \frac{\text{negative - sequence voltage}}{\text{positive - sequence voltage}} = \frac{V_2}{V_1}
\]

(9)

C. Harmonic distortion (HD)

The waveform distortion in a circuit under non-sinusoidal condition is given by

\[
a(t) = \sqrt{2} \sum_{h=1} A_h \sin(2\pi f_h t + \theta_h)
\]

(10)
where \( a(t) \) : instantaneous voltage \( V(t) \) or current \( I(t) \)
\( A_h \) : RMS of \( h \)th order harmonic
\( f_h \) : frequency of \( h \)th order harmonic
\( \theta_h \) : angle of \( h \)th order harmonic

Then, the total harmonic distortion is given by

\[
THD(\%) = \sqrt{\sum_{h=2}^{\infty} \frac{A_h^2}{A_1^2}} \times 100\%
\]

### 4 Simulation Method and Results

This investigation employed the Matlab/Simulink and Matlab/SimPowerSystem to demonstrate the voltage deviation, voltage unbalance, and total harmonic distortion phenomenon. Figure 4 shows the simulation model. The simulation procedures are as follows.

1. The utility side is a symmetrical three-phase voltage source.
2. The three-phase to two-phase transformer is constructed by using corresponding windings with adequate turn ratios.
3. The loads on the two-phase side are composed of parallel RLC load. The parallel RLC load consists of active and reactive powers.
4. The RMS and instantaneous phase-to-phase voltages and line currents of the three-phase side can be obtained by the measurement blocks.
5. The nonlinear loads on the two-phase side are composed of power electrical equipments. The power electronic devices convert single-phase power into three-phase power by using AC-DC-AC PWM converter. Figure 5 shows the nonlinear loads in the simulation model.
6. The fundamental and harmonic components of the voltages and currents can be obtained by using the FFT calculation.
7. The voltage deviation, voltage unbalance, and total harmonic distortion factor are calculated.

The basic data of the system and the transformers are

1. The system short-circuit capacity on the 161-kV utility source (three-phase) is 10935MVA with \( X/R=33.25 \).
2. The \( TR_1 \) transformer is 200MVA and has the voltage ratio \( N_1 : N_2 = 161kV : 69kV \).
3. The capacity of the three-phase to two-phase transformer is 30 MVA on the primary side, and has the voltage ratio \( N_1 : N_2 = 69kV : 27.5kV \).
4. The transmission line \( Z_{L1}, Z_{L2M}, Z_{L2T}, \) Load M, Load T, and other data as shown TABLE 1.

#### TABLE 1 System Data

| Power Source | Three-phase balanced, 161kV, Y connected, X/R=33.25, MVA = 10935MVA. |
| Transformer | TR_1 : 161/69kV, 200MVA, X_{T1}=13%, X/R=40
\triangle/Y or Y-g connected, Z_{g1}=20Ω |
|            | TR_2 : 3Φ69/2Φ27.5kV, 30MVA, X_{T2}=10%, X/R=10, V-V, Scott or Le Blanc connected. |
| Line       | Z_{L1}=1.1869+j3.9108 Ω, Z_{L2T}=Z_{L2M}=0.97+j2.55 Ω |

The simulation results of a single-phases short-circuit fault on the second-phase side are shown in TABLE 2. Some observations can be obtained.

1. In case A1, the two secondary phases have equal loading. The voltage values of \( V_{ab}, V_{bc} \) and \( V_{ca} \) are the same in the Le Blanc scheme. The voltage unbalance values are different, and \( U_{sd2,\text{V-V}}>U_{sd2,\text{Scott}}>U_{sd2,\text{Le Blanc}} \).
2. In Case A2, the two secondary phases have light and equal loading. The voltage values are the same in the Scott and Le Blanc schemes, but different in the V-V scheme. The voltage unbalance values are different, and \( U_{sd2,\text{V-V}}>U_{sd2,\text{Scott}}>U_{sd2,\text{Le Blanc}} \).
3. There is a special unequal loading situation in Case A3. The two-phase side has same active power but opposite reactive power in phases M and T. The \( V_{bc} \) values of Scott and Le Blanc schemes are over 1 pu. The voltage unbalance values are different, and \( U_{sd2,\text{Scott}}>U_{sd2,\text{Le Blanc}}>U_{sd2,\text{V-V}} \).
4. In Case A4, the loading of phase T is heavy and that of phase M is light. The \( V_{ab} \) values of Scott and Le Blanc schemes are less than the \( V_{bc} \) and
$V_{ca}$. The voltage unbalance effects values are different, and $U_{sd2,V-V} > U_{sd2,Le_Blanc} > U_{sd2,Scott}$.

(5) In Case A5, the loading of phase $T$ is light and that of phase $M$ is heavy. The $V_{th}$ values of Scott and Le Blanc schemes are greater than the $V_{ca}$ and $V_{cb}$. The voltage unbalance effects values are different, and $U_{sd2,V-V} > U_{sd2,Le_Blanc} > U_{sd2,Scott}$.

The effects of nonlinear loads are examined in TABLE 3. The nonlinear loads can produce harmonic currents. Some observations can be obtained.

(1) In case B1, the two secondary phases have equal loading. The total harmonic distortion factors in the Le Blanc scheme are approximate. The $b_{phase}$ THDs of the Scott scheme are larger than $a_{phase}$ and $c_{phase}$. That $b_{phase}$ THD of current of the V-V scheme is smaller than $a_{phase}$ and $c_{phase}$, but THD of voltage is reverse.

(2) In Case B2, the two secondary phases have equal loading but nonlinear level is larger than Case B1. The THD values are greater than Case B1.

(3) A special unequal loading situation is given in Case B3. The $b_{phase}$ total harmonic distortion factors in the Scott and Le Blanc schemes are much larger than that of $a_{phase}$ and $c_{phase}$. But it is reverse in the V-V scheme.

(4) In Case B4 the loading of phase $T$ is heavy and that of phase $M$ is light. The $b_{phase}$ total harmonic distortion factors of current in the Scott and Le Blanc schemes are much larger than that of $a_{phase}$ and $c_{phase}$, but reverse in the V-V scheme. The $b_{phase}$ THDs of voltage in the V-V and Scott schemes are larger than $a_{phase}$ and $c_{phase}$, but that in the Le Blanc scheme is $a_{phase}$.

(5) In Case B5, the loading of phase $M$ is heavy. The $b_{phase}$ total harmonic distortion factors of current of three schemes are smaller than $a_{phase}$ and $c_{phase}$. The $c_{phase}$ THDs of voltage in the Scott and Le Blanc schemes are larger than $a_{phase}$ and $b_{phase}$. It is reverse in the V-V scheme.

5 Conclusion

The model of nonlinear loads to examine the effects of nonlinear on the specially connected transformer is given in this paper. The power electrical equipments are used. Through these studies, the power quality characteristics of the V-V, Scott, and Le Blanc connected transformers are compared. Form the computation results, the Le Blanc connected transformer could have better power quality level. The V-V connection scheme has larger voltage unbalance values than that of the Scott and Le Blanc connection schemes. In single-phase short-circuit fault studies, the Le Blanc connection scheme has larger voltage unbalance values.

References

### TABLE 2 Comparison of Power Quality Factor Values in Case A

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<tr>
<th>Connection scheme</th>
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### TABLE 3 Comparison of Power Quality Factor Values in Case B

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