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PART B

Contents:

(continued from Part A)

On Some Numerical Methods for the Non Linear Transport Equation in 3D 255
by Abdallah Tamrabet, Abdelouahab Kadem

Multi-Scale Multi-Physics Modeling of Bundled Multiwalled Carbon Nanotube Interconnects 262
by Omar F. Mousa, Jaber A. Abu Qahouq

Electromagnetic Analysis of Railguns by Numerical Simulations 270
by Mehdi Peyvandi, Mehrdad Jafarboland, Mohsen Zafarani

Discrete Wavelet Decomposition Applied to Position Sensor Default Detection on a PMSM Traction Drive 279
by Manef Bourogaoui, Houda Ben Attia Sethom

Multiobjective Optimal Design of Transformer Using Bacterial Foraging Algorithm 287
by S. Subramanian, S. Padma

Transient-State Modeling of Distribution Transformers 295
by Mehdi Bigdeli, Ebrahim Rahimpour, Masoud Khatibi

Improve the Performance of Linear Induction Motors by Independent Control for Testing Aircraft and Submarine Models 303
by Abdolamir Nekoubin

Parameter Estimation of Three Phase Transformer Based on Bacterial Foraging Algorithm 310
by S. Subramanian, S. Padma

Application of D-STATCOM to Improve the Power Quality and Transient Operation of Induction Motor 318
by Amin Sarijali, Murtaza Farsadi

Models and Simulations for Reconfigurable Magnetic-Coupling Thrusters Technology 325
by O. Chocron, H. Mangel

Computation of the Parameters of a Slot-Embedded Conductor Using the Finite Element Formulation of the Impedance Boundary Condition 335
by A. M. El-Sawy Mohamed

Modeling and Comparison of Traction Transformers Based on the Utilization Factor Definitions 342
by Mohsen Kalantari, Mohammad Javad Sadeghi, Siamak Farshad, Seyed Saeed Fazel

(continued on inside back cover)

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Modeling and Comparison of Traction Transformers Based on the Utilization Factor Definitions

Mohsen Kalantari, Mohammad Javad Sadeghi, Siamak Farshad, Seyed Saeed Fazel

Abstract – *Electric railways inject undesirable harmonics and large negative sequence component to the utility grid due to their essential characteristics (i.e. non-linear, non-sinusoidal, non-symmetrical, and non-continuity). Traction transformers with a special connection (i.e. Single-phase, V/V, Wye-Delta, Scott, and Le-Blanc) are one of the best solutions to limit the above drawbacks and also improve the efficiency and power factor of the utility grid. They have been selected on the basis of electrical performance, physical profile of the network, and economics issues. Traction load variation, negative sequence component, load harmonic currents, power factor, and efficiency as effective electrical parameters were investigated for aforementioned traction transformers. However, there are other influential and important parameters in the electrical railway systems which are not considered in the research works. Therefore, this paper defines these factors (utilization factors of the traction transformer and transmission line) as mathematical equations and then investigates the impacts of harmonic components and unbalance loading on these factors.* ***Copyright © 2011 Praise Worthy Prize S.r.l. - All rights reserved.***

***Keywords**: Traction Transformer, Unbalance Loading, Line Utilization Factor, Transformer Utilization Factor*

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Nomenclature

TDD	Total demand distortion
PCC	Point of common coupling
S_R	Maximum Capacity Utilization
S_T	Transformer Capacity
S_L	Line Capacity
I_x, V_x (x=A, B, C)	Primary currents and voltages
I_y, V_y (y=R, L)	Secondary currents and voltages
TUF	Transformer Utilization Factor
LUF	Line Utilization Factor
S_A, S_B and S_C	Three phases of the utility grid
BD	Balance degree

I. Introduction

An electric feeding power substation feed the non-linear and time-varying single phase traction load which serves large negative sequence component, undesirable harmonic currents and unacceptable total demand distortion (*TDD*) to the utility grid [1]. To balance the traction load, traction substations are fed at equal section (*i.e. RS* phases, *ST* phases, *TR* phases respectively). However, the large voltage and current unbalanced may be seen in the utility grid, if the traction loads are running only in a particular section. Therefore, the large unbalanced traction loads may significantly affect the operation of the utility grid and other connected loads to it.

These problems may be also caused additional system losses, overheat rotating machine, and malfunction of the protection relays and measuring instruments. These problems reduce the transportation capacity of the traction transformers and electrical transmission lines.

The traction transformers with special connections (*i.e.* Single-phase, V/V, Wye-Delta, Scott, and Le-Blanc) are employed to limit aforementioned effects and also improve the efficiency and power factor at the point of common coupling (*PCC*) [2], [3]. For example, the Single-phase connection is used in Italian railways, French *TGV*, and New Zealand railways [4]. The V/V connection is used in French *TGV*, British railways, and Finnish railways [4]. The Wye-Delta connection is used in China railways and finally the Scott and Le-Blanc connections are used in Japanese and Taiwan railways respectively [4]. The Scott transformer was first applied for the power conversion of two phase generators at a hydro generation plant located at Niagara Falls, NY, in 1896 [5], [6]. The Le-Blanc transformer has been applied to electric power engineering since the end of the 19th century, but is not as popular as the Scott connection [7].

Recent studies concerning the specially connected transformers have been emphasized on several topics, such as modeling for particular studies, evaluating voltage unbalance, discussing the effect of harmonics, and revising the differential protection methods. For example, simplified models of specially connected transformers have been applied in three phase power flow studies [8]. A network model was proposed to study unbalanced effects [9]. Specially connected transformers

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based on the physical three phase circuits and the symmetrical component equivalent circuits have been modeled in detail [4]. A rigorous method to evaluate the voltage unbalance due to specially connected transformers has been proposed [10]. The harmonic problems of Le-Blanc transformers for the Taiwan Railway electrification system were studied in [11]. The effects of the harmonic and negative sequence components of voltage and current and also power factor at the *PCC* have been evaluated in [11]-[15], [2] respectively. However, the utilization factors of the transformer and transmission line have not been analyzed sufficiently in the electric railway systems. This paper initially introduces the definitions of the utilization factors and then, evaluates the impacts of several important and influential parameters on these factors.

II. Utilization Factor Definitions

Unbalance loading is one of the significant problems in electric railway systems, which causes a part of the network capacity unusable. So, to feed the traction loads in unbalanced mode, the installed capacity should be considered more than estimated ones. It is remarkable that the required investment costs for network construction significantly enhance when increasing the ratio of the installed capacity to the load. Therefore, to reduce the investment costs, this ratio should be controlled in unbalanced condition. Traction transformers and three phase transmission line are two affecting parameter on the construction and investment costs. Hence, the transformer and transmission line utilization factors are defined as indices to evaluate the actual required capacity.

To calculate the utilization factor for different special transformers, the simplified circuit diagram of an electrified railway is considered (see Figs. 1) and the following definition are also used:

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II.1. Maximum Capacity Utilization (S_R)

This parameter represents the maximum capacity utilization of the utility grid including the traction transformer and transmission line. It is influenced by the load harmonics as well as the unbalance loading and can be calculated by the following equation:

$$S_R = S_A + S_B + S_C \tag{1}$$

where S_A, S_B, S_C are the phase apparent powers.

II.2. Transformer Capacity (S_T)

The transformer capacity is calculated considering maximum load balance condition. This parameter can be computed as follows:

$$S_T = \sum_{j=1}^{\infty} S_j \tag{2}$$

where, S_j is the transformer winding capacity.

II.3. Line Capacity (S_L)

This parameter is computed as follows assuming maximum load balance demand, where I_{MAX} is the maximum calculated current between three phase currents (*A*, *B*, *C*):

$$S_L = 3VI_{MAX}^{\ *} \tag{3}$$

According to the above definitions, the Transformer Utilization Factor (*TUF*) and the Line Utilization Factor (*LUF*) can be defined as follows:

$$TUF = \frac{S_R}{S_T} \tag{4}$$

$$LUF = \frac{S_R}{S_L} \tag{5}$$

The effects of unbalance loading and harmonic distortions on the utilization factors also investigated based on equations ((6)-(10)) [16]:

$$V(t) = V_0 + \sqrt{2}\sum_{h\neq 0}^{\infty} V_h \sin(hwt + \alpha_h) \tag{6}$$

$$I(t) = I_0 + \sqrt{2}\sum_{h\neq 0}^{\infty} I_h \sin(hwt + \beta_h) \tag{7}$$

$$S = VI \tag{8}$$

$$\begin{cases} |I_R| \leq |I_L| \\ BD_1 = \dfrac{|I_R|}{|I_L|}\ ,\ 0\leq BD_1 \leq 1 \end{cases} \tag{9}$$

$$\begin{cases} |I_L| \leq |I_R| \\ BD_2 = \dfrac{|I_L|}{|I_R|}\ ,\ 0\leq BD_2 \leq 1 \end{cases} \tag{10}$$

where, *V* and *I* denote the effective phase voltage and phase current, respectively. BD_1, BD_2 are balance degrees at the both secondary sides of substation and *S* is the apparent power at the single phase system.

All investigations in the following sections only done based on the BD_1 due to identical simulation results for both balance degrees.

The calculation results are summarized in Table I.

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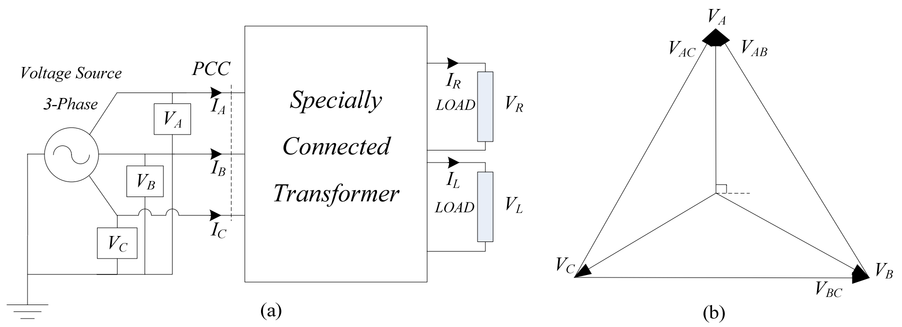

Figs. 1. (a) Block diagram of electrified railway network (b) Vector diagram of network voltages I_x, V_x ($x=A, B, C$): Primary currents and voltages; I_y, V_y ($y=R, L$): Secondary currents and voltages

III. Traction Transformer

III.1. Single-phase Connection

Fig. 2 shows the configuration of this connection. The output voltage, primary and secondary currents can be calculated using the following equations ((11)-(15)) respectively:

$$V_L = V_R = \frac{N_2}{N_1} V_{BC} = \frac{\sqrt{3} N_2}{N_1} V e^{i0} = E e^{i0} \tag{11}$$

$$I_A = 0 \tag{12}$$

$$I_B = -I_C = I_H + I_F = \frac{N_2}{N_1}\left(1+BD\right) I e^{-i\theta} \tag{13}$$

$$I_L = I e^{-i\theta} \tag{14}$$

$$I_R = BD\, I e^{-i\theta} \tag{15}$$

The apparent powers of the three phases of the utility grid (S_A, S_B *and* S_C), the maximum capacity utilization (S_R), and the transformer winding capacity ($S_1 = S_2$), the transformer capacity (S_T), and the line capacity (S_L) can be computed respectively as follows:

$$S_A = 0 \tag{16}$$

$$S_B = \frac{\left(1+BD\right) EI}{\sqrt{3}} e^{i(\theta-\frac{\pi}{6})} \tag{17}$$

$$S_C = \frac{\left(1+BD\right) EI}{\sqrt{3}} e^{i(\theta+\frac{\pi}{6})} \tag{18}$$

$$S_R = \left|S_A + S_B + S_C\right| = \left(1+BD\right) EI \tag{19}$$

$$S_1 = S_2 = EI e^{i\theta} \tag{20}$$

$$S_T = \left|S_1\right| + \left|S_2\right| = 2EI \tag{21}$$

$$S_L = \left|3 V_B I_B^{*}\right| = 2\sqrt{3} EI \tag{22}$$

The line capacity (S_L) computes based on the I_B or I_C which is equal to the maximum current of the utility grid.

III.2. V/V Connection

Fig. 3 shows the configuration of this connection. The output voltage, primary and secondary currents can be calculated using the following equations (23-29) respectively:

$$V_R = \frac{N_2}{N_1} V_{BC} = \frac{\sqrt{3} N_2}{N_1} V e^{i0} = E e^{i0} \tag{23}$$

$$V_L = \frac{N_2}{N_1} V_{AC} = \frac{\sqrt{3} N_2}{N_1} V e^{i\frac{\pi}{3}} = E e^{i\frac{\pi}{3}} \tag{24}$$

$$I_A = \frac{N_2}{N_1} I e^{i\left(\frac{\pi}{3}-\theta\right)} \tag{25}$$

$$I_B = \frac{N_2}{N_1} I_R = \frac{N_2}{N_1} BD\, I e^{-i\theta} \tag{26}$$

$$I_C = -\left(I_A + I_B\right) \tag{27}$$

$$I_L = I e^{i\left(\frac{\pi}{3}-\theta\right)} \tag{28}$$

$$I_R = BD\, I e^{-i\theta} \tag{29}$$

Three phase apparent powers of the utility grid (S_A, S_B *and* S_C), the maximum capacity utilization (S_R), and the transformer winding capacity ($S_1 = S_2$), the maximum transformer capacity (S_T), respectively as follows:

$$S_A = \frac{E}{\sqrt{3}} I e^{i\left(\theta+\frac{\pi}{6}\right)} \tag{30}$$

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$$S_B = \frac{E}{\sqrt{3}} BD\, I e^{i\left(\theta - \frac{\pi}{6}\right)} \quad (31)$$

$$S_C = \frac{E}{\sqrt{3}} I \left(1e^{i\left(\theta - \frac{\pi}{6}\right)} + BD\, e^{i\left(\theta + \frac{\pi}{6}\right)} \right) \quad (32)$$

$$S_R = \left| S_A + S_B + S_C \right| = \left(1 + BD\right) EI \quad (33)$$

$$S_1 = S_2 = EIe^{i\theta} \quad (34)$$

According to Figs. 3, the computation of the maximum transformer capacity (S_T) in this connection is similar to the Single-phase transformer. It calculates using algebraic summation of the both transformer winding capacity under balance load conditions at the both secondary sides of the power substation. The line capacity (S_L) computes based on the I_C which is equal to the maximum current of the utility grid:

$$S_T = \left| S_1 \right| + \left| S_2 \right| = 2EI \quad (35)$$

$$S_L = \left| 3V_C I_C^{\,*} \right| = 3EI \quad (36)$$

III.3. Wye-Delta Connection

The presented equations in this section are related only to the three phase transformer with vector group of one (*yd1*). These relations can be generalized for other vector group.

Figs. 4 show the configuration of this connection. The output voltage, primary and secondary currents can be calculated using the following equations ((37)-(43)) respectively:

$$V_R = V_{cb} = Ee^{i\frac{5\pi}{6}} \quad (37)$$

$$V_L = V_{ab} = Ee^{i\frac{\pi}{2}} \quad (38)$$

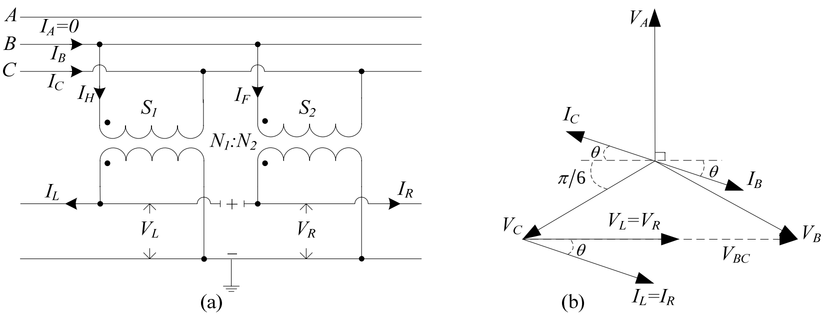
$$I_A = \frac{N_2 I}{3N_1} \left(2e^{i\left(\frac{\pi}{2} - \theta\right)} + BD\, e^{i\left(\frac{5\pi}{6} - \theta\right)} \right) \quad (39)$$

$$I_B = \frac{N_2 I}{3N_1} \left(1e^{i\left(-\frac{\pi}{2} - \theta\right)} + 2BD\, e^{i\left(-\frac{\pi}{6} - \theta\right)} \right) \quad (40)$$

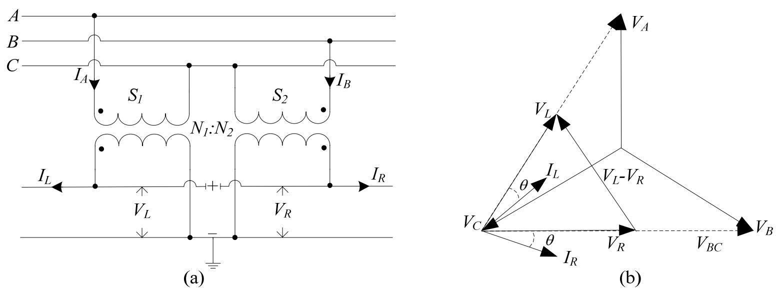
$$I_C = \frac{N_2 I}{3N_1} \left(1e^{i\left(-\frac{\pi}{2} - \theta\right)} + BD\, e^{i\left(\frac{5\pi}{6} - \theta\right)} \right) \quad (41)$$

$$I_L = I_{ab} - I_{ca} = Ie^{i\left(\frac{\pi}{2} - \theta\right)} \quad (42)$$

$$I_R = I_{ca} - I_{bc} = BD\, Ie^{i\left(\frac{5\pi}{6} - \theta\right)} \quad (43)$$



Figs. 2. The configuration of the Single-phase traction transformer (a) Structure, (b) Phasor diagram



Figs. 3. The configuration of the V/V traction transformer (a) Structure, (b) Phasor diagram

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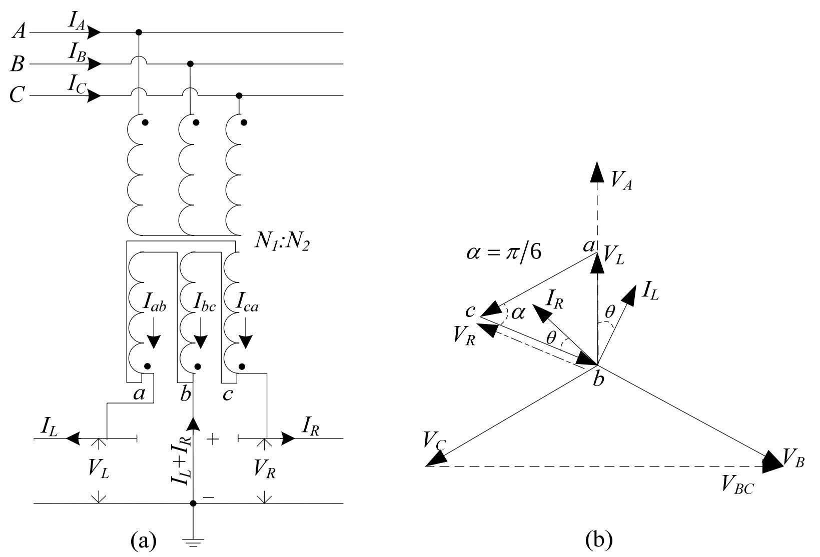

Figs. 4.The configuration of the Wye-Delta traction transformer (a) Structure, (b) Phasor diagram

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Three phase apparent powers of the utility grid (S_A, S_B *and* S_C), the maximum capacity utilization (S_R) respectively as follows:

$$S_A = \frac{EI}{3}\left(2e^{i\theta} + BD\,e^{i\left(\theta-\frac{\pi}{3}\right)}\right) \quad (44)$$

$$S_B = \frac{EI}{3}\left(1e^{i\left(\theta+\frac{\pi}{3}\right)} + 2BD\,e^{i\theta}\right) \quad (45)$$

$$S_C = \frac{EI}{3}\left(1e^{i\left(\theta-\frac{\pi}{3}\right)} + BD\,e^{i\left(\theta+\frac{\pi}{3}\right)}\right) \quad (46)$$

$$S_R = \left|S_A + S_B + S_C\right| = \left(1 + BD\right)EI \quad (47)$$

The amplitude of the *A* and *B* phase currents are the same and also equal with the maximum network current in balance conditions. The maximum capacities of transformer (S_T) and line (S_L) are too similar according to Figs. 4:

$$S_L = S_T = \left|3V_j I_j^*\right| = \left|2e^{i\theta} + 1e^{i\left(\theta-\frac{\pi}{3}\right)}\right| EI = 2.64EI \quad (48)$$

where $j = A$ or B.

III.4. Scott Connection

Figs. 5 shows the configuration of this connection. The output voltage, primary and secondary currents can be calculated using the following equations ((49)-(58)) respectively:

$$V_{AO} = \frac{\sqrt{3}}{2}\left|V_{BC}\right| e^{i\frac{\pi}{2}} = \frac{3}{2}Ve^{i\frac{\pi}{2}} \quad (49)$$

$$V_{BO} = \frac{1}{2}\left|V_{BC}\right| e^{i0} = \frac{\sqrt{3}}{2}\mathrm{V}e^{i0} \quad (50)$$

$$V_{CO} = \frac{1}{2}\left|V_{BC}\right| e^{i\pi} = \frac{\sqrt{3}}{2}\mathrm{V}e^{i\pi} \quad (51)$$

$$V_R = \frac{N_2}{N_1}V_{BC} = Ee^{i0} \quad (52)$$

$$V_L = \frac{N_2}{\frac{\sqrt{3}}{2}N_1}V_{AO} = Ee^{i\frac{\pi}{2}} \quad (53)$$

$$I_A = \frac{2N_2}{\sqrt{3}N_1}Ie^{i\left(\frac{\pi}{2}-\theta\right)} \quad (54)$$

$$I_B = \frac{N_2}{N_1}I\left[BD\,e^{-i\theta} + \frac{\sqrt{3}}{3}e^{i\left(-\frac{\pi}{2}-\theta\right)}\right] \quad (55)$$

$$I_C = \frac{N_2}{N_1}I\left[BD\,e^{i(\pi-\theta)} + \frac{\sqrt{3}}{3}e^{i\left(-\frac{\pi}{2}-\theta\right)}\right] \quad (56)$$

$$I_L = Ie^{i\left(\frac{\pi}{2}-\theta\right)} \quad (57)$$

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$$I_R = BD\,Ie^{-i\theta} \tag{58}$$

Three phase apparent powers of the utility grid (S_A, S_B, *and* S_C), the maximum capacity utilization (S_R) respectively as follows:

$$S_A = \frac{2}{3}EIe^{i\theta} \tag{59}$$

$$S_B = \frac{EI}{\sqrt{3}}\left(BD_1 e^{i\left(\theta-\frac{\pi}{6}\right)} + \frac{\sqrt{3}}{3}e^{i\left(\theta+\frac{\pi}{3}\right)}\right) \tag{60}$$

$$S_C = \frac{EI}{\sqrt{3}}\left(BD_1 e^{i\left(\theta+\frac{\pi}{6}\right)} + \frac{\sqrt{3}}{3}e^{i\left(\theta-\frac{\pi}{3}\right)}\right) \tag{61}$$

$$S_R = \left|S_A + S_B + S_C\right| = \left(1 + BD_1\right)EI \tag{62}$$

The summation of primary windings capacities (S_{AO}, S_{BO}, *and* S_{CO}) is about 8 percent larger than the summation of secondary windings capacities (S_R, S_L) and therefore, it is considered as the base to evaluate the transformer capacity:

$$S_{AO} = V_{AO}I_A^{\,*} = EIe^{i\theta} \tag{63}$$

$$S_{BO} = V_{BO}I_B^{\,*} = \frac{EI}{2}\left(BD\,e^{i\theta} + \frac{\sqrt{3}}{3}e^{i\left(\theta+\frac{\pi}{2}\right)}\right) \tag{64}$$

$$S_{CO} = V_{CO}I_C^{\,*} = \frac{EI}{2}\left(BD\,e^{i\theta} + \frac{\sqrt{3}}{3}e^{i\left(\theta-\frac{\pi}{2}\right)}\right) \tag{65}$$

$$S_R = V_R I_R^{\,*} = EI\left(BD\,e^{i\theta}\right) \tag{66}$$

$$S_L = V_L I_L^{\,*} = EIe^{i\theta} \tag{67}$$

$$S_T = \left|S_{AO}\right| + \left|S_{BO}\right| + \left|S_{CO}\right| = \frac{3+2\sqrt{3}}{3}EI \tag{68}$$

Due to balanced structure of this connection, all three phase current amplitudes are equal in load balance condition and then, the maximum line capacity can be estimated as follows:

$$S_L = \left|3V_j I_j^{\,*}\right| = 2EI \tag{69}$$

where $j = A$ or B or C .

III.5. Le-Blanc Connection

Figs. 6 show the configuration of this connection. The output voltage, primary and secondary currents can be calculated using the following equations ((70)-(76)) respectively:

$$V_L = \sqrt{3}\frac{N_2}{N_1}Ve^{-i\frac{\pi}{2}} = Ee^{-i\frac{\pi}{2}} \tag{70}$$

$$V_R = \sqrt{3}\frac{N_2}{N_1}Ve^{i0} = Ee^{i0} \tag{71}$$

$$I_A = I_{ab} - I_{ca} = \frac{2N_2}{\sqrt{3}N_1}Ie^{i\left(\frac{\pi}{2}-\theta\right)} \tag{72}$$

$$I_B = I_{bc} - I_{ab} = \frac{N_2}{N_1}I\left[\frac{\sqrt{3}}{3}e^{i\left(-\frac{\pi}{2}-\theta\right)} + BD\,e^{-i\theta}\right] \tag{73}$$

$$I_C = I_{ca} - I_{bc} = \frac{N_2}{N_1}I\left[\frac{\sqrt{3}}{3}e^{i\left(-\frac{\pi}{2}-\theta\right)} - BD\,e^{-i\theta}\right] \tag{74}$$

$$I_L = Ie^{i\left(-\frac{\pi}{2}-\theta\right)} \tag{75}$$

$$I_R = BD\,Ie^{-i\theta} \tag{76}$$

Three phase apparent powers of the utility grid (S_A, S_B, *and SC*), the maximum capacity utilization (S_R) respectively as follows:

$$S_A = \frac{2}{3}EIe^{i\theta} \tag{77}$$

$$S_B = \frac{EI}{\sqrt{3}}\left[BD_1 e^{i\left(\theta-\frac{\pi}{6}\right)} + \frac{\sqrt{3}}{3}e^{i\left(\theta+\frac{\pi}{3}\right)}\right] \tag{78}$$

$$S_C = \frac{EI}{\sqrt{3}}\left[BD_1 e^{i\left(\theta-\frac{\pi}{6}\right)} + \frac{\sqrt{3}}{3}e^{i\left(\theta-\frac{\pi}{3}\right)}\right] \tag{79}$$

$$S_R = \left|S_A + S_B + S_C\right| = \left(1 + BD_1\right)EI \tag{80}$$

The summation of secondary windings capacities (S_1, S_2, S_3, S_4, *and* S_5) is about 25 percent larger than the summation of primary windings capacities (S_{AB}, S_{BC}, *and* S_{CA}) and therefore, it is considered as the base to evaluate the transformer capacity:

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$$S_{AB} = V_{AB} I_{AB}^{*} = EI\left[\frac{\sqrt{3}}{3} e^{i\left(\theta+\frac{\pi}{6}\right)} + \frac{BD_1}{3} e^{i\left(\theta-\frac{\pi}{3}\right)}\right] \quad (81)$$

$$S_{BC} = V_{BC} I_{BC}^{*} = EI\left[\frac{\sqrt{3}}{3} e^{i\left(\theta-\frac{\pi}{6}\right)} + \frac{BD_1}{3} e^{i\left(\theta+\frac{\pi}{3}\right)}\right] \quad (82)$$

$$S_{CA} = V_{CA} I_{CA}^{*} = EI\left[\frac{2BD_1}{3} e^{i\theta}\right] \quad (83)$$

$$S_1 = \frac{EI}{\sqrt{3}} e^{i\left(\theta-\frac{5\pi}{6}\right)} \quad (84)$$

$$S_2 = \frac{BD_1}{3} EIe^{i\left(\theta+\frac{2\pi}{3}\right)} \quad (85)$$

$$S_3 = \frac{2BD_1}{3} EIe^{i\theta} \quad (86)$$

$$S_4 = \frac{EI}{\sqrt{3}} e^{i\left(\theta-\frac{\pi}{6}\right)} \quad (87)$$

$$S_5 = \frac{BD_1}{3} EIe^{i\left(\theta-\frac{2\pi}{3}\right)} \quad (88)$$

$$S_T = \left|S_1\right| + \left|S_2\right| + \left|S_3\right| + \left|S_4\right| + \left|S_5\right| = \frac{4+2\sqrt{3}}{3} EI \quad (89)$$

Due to the balanced structure of this connection, all three phase current amplitudes are equal and then, the maximum line capacity can be estimated as follows:

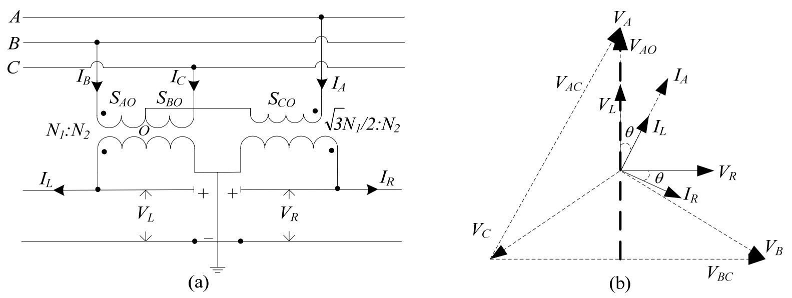
$$S_L = \left|3V_j I_j^{*}\right| = 2\text{EI} \quad (90)$$

where $j = A$ or B or C.

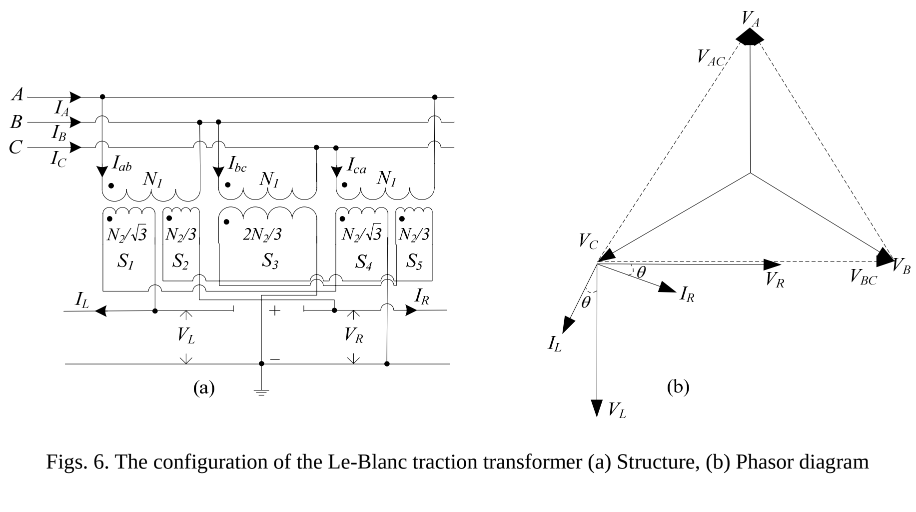
IV. Simulation and Analysis Results

The effects of the harmonic distortions and also unbalance loading on the transformer and line utilization factors need to be carefully considered. The following operating conditions are assumed throughout this paper:

1) The traction load is modeled by an electrical resistive-inductive (*RL*) load. It is accepted that both side of the traction transformer feeds equivalently this load (P_R=P_L=6MW, Q_R=Q_L=3.6MVAr).
2) The input data of the selected network is summarized in Table I.



Figs. 5. The configuration of the Scott traction transformer (a) Structure, (b) Phasor diagram



Figs. 6. The configuration of the Le-Blanc traction transformer (a) Structure, (b) Phasor diagram

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TABLE I
THE NECESSARY INPUT DATA

Symmetrical Voltage Source	69 kV
Short-Circuit Capacity on the primary (three phase) side	2736 MVA
Transformer Capacity	15 MVA
Turn ratio no load (*N1:N2*)	69:27.5

Two following different cases are discussed in the following sections.

IV.1. The Effects of Harmonic Distortion on the TUF and LUF

The effects of the harmonic distortions including variable third, fifth, seventh harmonic orders from zero to 40% on the *TUF* and *LUF* are shown in Figs. 7. This figure shows that the harmonic components are not affected on the *TUF* for all investigated transformer connections (Fig. 7(a)).

Furthermore, the behavior and also the amount of the *TUF* for both Single-phase and V/V connections are the same in the entire harmonic components range. However, the harmonic components would be caused a little variation on the *LUF* as depicted in Fig. 7(b).

IV.2. The Effects of Unbalance Loading on the TUF and LUF

In this step, the load is varied from complete balance condition (considering the same load in both side of the traction transformer) to complete unbalance condition. Figs. 8 shows the behavior of the *TUF* and *LUF* as a function of the unbalance degree (*1-BD*).

The simulation results show that the *TUF* and *LUF* are decreased by reducing the balance degree (*BD*) from unity to zero for all investigated transformer connections.

Therefore, the impact of the unbalance degree (*1-BD*) on the *TUF* (especially for Single-phase and V/V connections) and L*U*F (especially for Scott and Le-Blanc connections) are the same for all considered transformer connections (Fig. 8(a) and Fig. 8(b)).

The calculation results of the *TUF* and *LUF* based on balance degree (*BD*) are summarized in Table II for the aforementioned transformer connections.

It is obvious that Single-phase and V/V connections enable the maximum *TUF* (100 percent) at the complete balance loading while the Wey-Delta connection realizes the minimum *TUF* compared to other connections. However, the Wey-Delta connection is the common connection which uses in power system networks and therefore, it features fewer cost in comparison to the other transformer connections.

It is interesting to note that the Scott and Le-Blanc connections generate more utilization factor respectively compared to Wey-Delta connection due to better balanced structure. However, these types of connections are more complicated and also expensive in respect to other connections.

It is interesting to note that the *LUF* was computed for Single-phase connection assuming three wire transmission lines.

It is evident that the result can be similar for Single-phase and V/V connections considering two wire transmission line. The results show that the Le-Blanc, Scott, Wye-Delta, V/V, and Single-phase connections enable higher *LUF* respectively achieving in complete balance loading. The *LUF* decreases when the length of the transmission line increased which affects on the required investment costs for transmission line construction.

In conclusion, the low *TUF* and *LUF* and also other cost-causing in Wey-Delta transformer connection limits its application in electrical railway system compared to other types of the traction transformers.

In cases where a long transmission line is needed and its cost is significant comparable to the traction transformer cost, the Scott and Le-Blanc traction transformers are recommended to reduce the overall costs and also negative sequence currents.

Otherwise, the use of V/V and Single-phase connections would be decreased the total costs compared to other types of the traction transformers.

TABLE II
THE UTILIZATION FACTORS OF TRANSFORMER AND TRANSMISSION LINE FOR FIVE TYPES OF TRACTION TRANSFORMERS

Traction Transformers	Single-phase	V/V	Wey-Delta	Scott	Le-Blanc
TUF	$\frac{1+BD}{2}$	$\frac{1+BD}{2}$	$\frac{1+BD}{2.64}$	$\frac{3(1+BD)}{3+2\sqrt{3}}$	$\frac{3(1+BD)}{4+2\sqrt{3}}$
LUF	$\frac{(1+BD)}{2\sqrt{3}}$	$\frac{1+BD}{3}$	$\frac{1+BD}{2.64}$	$\frac{1+BD}{2}$	$\frac{1+BD}{2}$

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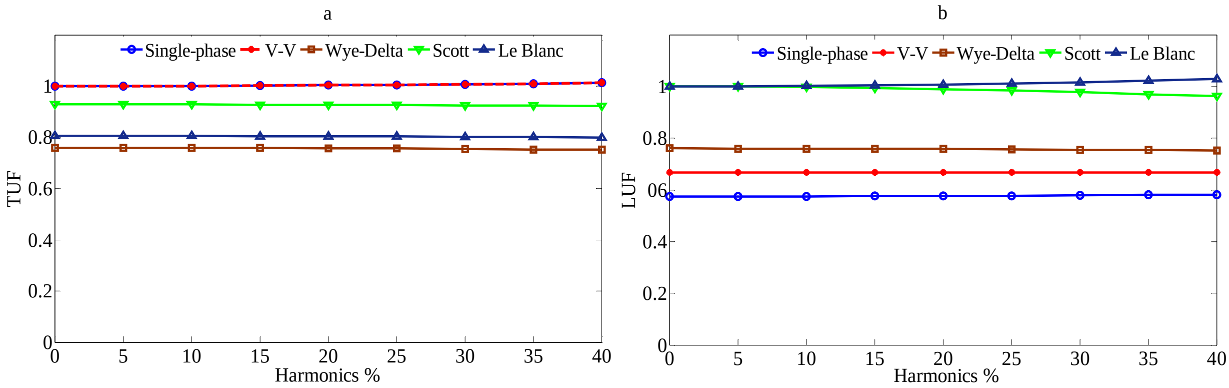
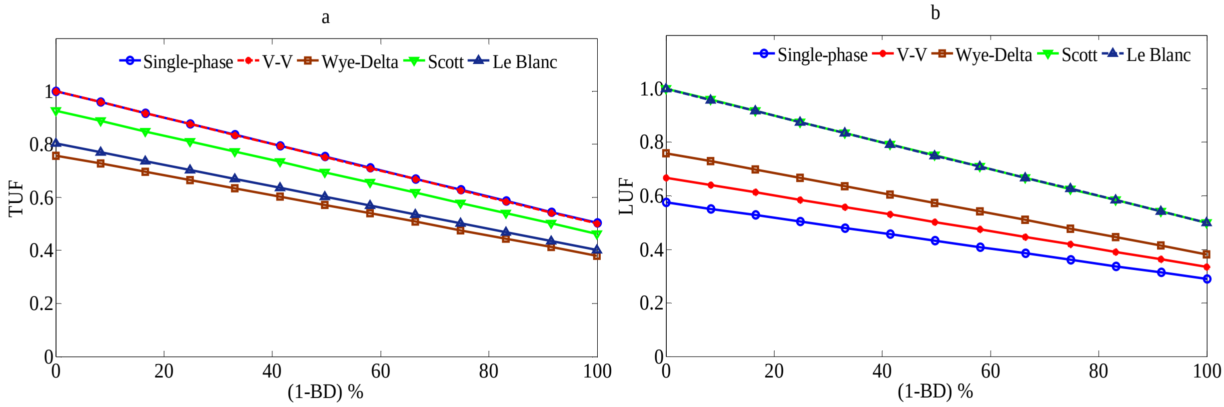


Figs. 7. The effects of the harmonic components on the *TUF* and *LUF*



Figs. 8. The effects of the unbalance degree (*1-BD*) on the *TUF* and *LUF*

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V. Conclusion

Electric railways inject undesirable harmonics and large negative sequence component to the utility grid due to their essential characteristics. Traction transformers with a special connection are one of the best solutions to limit their effects and also improve the efficiency and power factor of the utility grid. The impacts of harmonics components and unbalance loading have been investigated on the utilization factor which is the influential parameter in the electrical railway system.

To evaluate the performance of the electrical railway networks, the effect of harmonic distortion and unbalance loading on the *TUF* and *LUF* have been studied in detail and the simulation results have been compared regarding different traction transformer connections.

In the first comparison, the effects of harmonic distortions on the *TUF* and *LUF* have been examined considering the same load in both side of the traction transformer. The simulation results show that the harmonic components are not affected on the *TUF* for all investigated transformer connections. Furthermore, the behavior and also the amount of the *TUF* for both Single-phase and V/V connections are the same in the entire harmonic components range. However, the harmonic components would be caused a little variation on the *TUF* and *LUF*.

In the second comparison, the effects of the unbalance loading on the *TUF* and *LUF* have been investigated assuming load variation from complete balance condition to complete unbalance condition. The simulation results illustrate that the Single-phase and V/V connections could enable the maximum *TUF* (100 %) at the complete balance loading while the Wey-Delta connection realized the minimum ones (75 %) compared to other connections. The Le-Blanc, Scott, Wey-Delta, V/V, and Single-phase connections featured higher *LUF* respectively achieving in complete balance loading.

The low *TUF* and *LUF* and also other cost-causing in Wey-Delta transformer connection limited its application in electrical railway system compared to other types of traction transformer. In cases where a long transmission line is needed and its cost is significant comparable to the traction transformer cost, the Scott and Le-Blanc traction transformers provided the minimum overall costs and also negative sequence currents. Otherwise, the use of V/V and Single-phase connections decreased the total costs compared to other types of the traction transformers.

It is interesting to note that the unbalance loading increased with increasing the headway of trains in a certain track. In this case, the Single-phase connection would be economical type of the traction transformers due to its acceptable *LUF* and high *TUF* even in long transmission lines.

In conclusion, the *TUF* and *LUF* could be decreased about 50% by reducing the unbalance index from unity to zero for all investigated transformer connections.

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(continued from outside front cover)

Analysis of UPQC with Super-Capacitor to Power Quality Enhancement and Energy Storage 352
by S. Sajedi, T. Karimi, F. Khalifeh, Z. Khalifeh

Modeling and Simulation of Centrifugal Gas Compressor Using Adaptive Neuro-Fuzzy Inference System: Application to the Modeling and Simulation of the Industrial Packages 358
by Mohsen Hayati, Seyd Mohammad Jamshidi, Abbas Rezaei

Theoretical Investigation on the Thermal Performance of Two-Phase Heat Spreaders Including Parallel Microchannels 364
by J. Mansouri, S. Maalej, M. B. H. Sassi, M. C. Zaghdoudi

X-FEM Method for Crack Growth Modelling: Concepts and Computer Implementation 380
by Y. Abdelaziz, R. Abderrahmani, A. Chabani, T. Rikioui

Degenerated Finite Element Modelling: Effect of Size 388
by Y. Abdelaziz, R. Abderrahmani, A. Chabani, T. Rikioui

Robust Maximum Power Point Tracking for Fast Changing Environmental Conditions 391
by H. Abouobaida, M. Cherkaoui, M. Ouassaid

Using H∞ State Estimation for a Cold Flow Circulating Fluidized Bed on Standpipe 397
by Seyed Mohammad Hossein Nabavi, Nima Yoosef Pour, Somayeh Hajforoosh, Ali Jalali

Finite-Element Simulation of Heat Generation by Laser in Welding 403
by Ali Moarrefzadeh

Effects Clamped-Clamped Boundary Conditions for Vibration of Functionally Graded Cylindrical Shells Based on T.S.D.T. Using Hamilton's Principle 409
by M. R. Isvandzibaei

Shape and Dimension Estimation of Cracks Using Neural Network in Eddy Current Testing 417
by A. Babaei, S. Rafiei, A. Mrazeban, M. Saeidmanesh

Estimation of Location and Magnitude of Harmonic Sources by Optimal Measurement Placement 422
by S. Sajedi, F. Khlifeh, Z. Khalifeh, T. Karimi

Airflow Simulation of Particle Suction in Hard Disk Drives Manufacturing Process 429
by N. Yimsiriwatana, T. Jearsiripongkul

Temporal Neuro-Fuzzy Systems in Fault Diagnosis and Prognosis 436
by Mahdaoui Rafik, Mouss Leila Hayet, Mouss Med Djamel, Chouhal Ouahiba

A Hybrid State Space Model for Single Stage Three-Level Resonant Rectifiers 441
by Mohammed S. Agamy, Praveen K. Jain

Errata Corrige 457

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