Analysis of Six-pulse Rectifiers' Switching to Half-phase Mode

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Abstract: In contrast to the DC and single-phase AC electric traction systems existing on the electrified railways of the world, in the developed three-phase electric traction system, when one phase of power supply (one of two wires of contact network) is switched off, it becomes necessary to switch three-phase equipment of electric rolling stock, in particular six-pulse bridge rectifiers, into the partially phased mode. In this connection, the features of six-pulse bridge rectifiers operation are considered in this article. The instantaneous schemes of six-pulse bridge rectifiers operation in the partial phase mode and also vector diagrams of transformer secondary winding voltages connected by "star-delta" and "star-star" schemes in the full- and open phase modes of three-phase systems of traction power supply are presented. Based on the studies carried out, the relations of the connecting voltages, currents and powers of the considered six-pulse bridge rectifiers in the open phase mode are presented for both controlled and uncontrolled converters.

1 INTRODUCTION

Many countries are now actively developing new electric traction systems for mainline railways (Arzhannikov, 2015; Arzhannikov, 2019; Arzhannikov, 2019a; Belany, 2019; Chen, 2021; Fletcher, 2020; Frey, 2012; Jefimowski, 2018; Kaudia, 2017; Ľuptáka, 2020; Song, 2020; Tlili, 2020; Yang, 2019). A detailed analysis of such systems is performed in the monograph (Arzhannikov, 2019), according to which the most promising direction in this area is the three-phase power supply system (Belany, 2019).

The research conducted in (Arzhannikov, 2019) showed that when using three-phase electric traction system on the electrified sections of railways, it is necessary to switch the three-phase equipment of electric rolling stock, in particular six-pulse rectifiers, into an open phase mode. The present article is devoted to consideration of peculiarities of operation of these converters in this mode.

Description of processes occurring in six-pulse rectifiers will be made under the following assumptions:

1) active and reactive resistances of supplying network and converter transformer are equal to zero;
2) resistances of diodes in forward direction are equal to zero and in reverse direction are equal to infinity;
3) the load is a counter-EMF Ed and a smoothing reactor with inductive resistance equal to infinity $X_d = \infty$.

The phases of the primary windings are in capital letters and the phases of the secondary windings are in lower case letters.

2 MATERIALS AND METHODS

Rectifiers with full-phase operation correspond to the values without dashes, while the values with dashes correspond to the values with open phase operation.

When the load voltage changes, the inverter can operate according to several algorithms. We will consider two of them:

- Algorithm 1 - load remains constant regardless of rectified voltage (Z_d = const); this operating algorithm will correspond to the values with the index (A1);
- Algorithm 2 - the load is varied so that the incoming power remains constant ($P_d = U_d \cdot I_d$ = const); this operating algorithm will correspond to the values with the index (A2).

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Six-pulse converter circuit diagrams for star/delta connection of transformer windings (6Y/Δ) and star/star (6Y/Y) and are shown in Figures 1, a and b respectively. Each consists of a converter transformer T, with primary (PW) and secondary (SW) windings connected in delta respectively (SW Δ) or star (SW Y), and six diodes (VD1 — VD6).

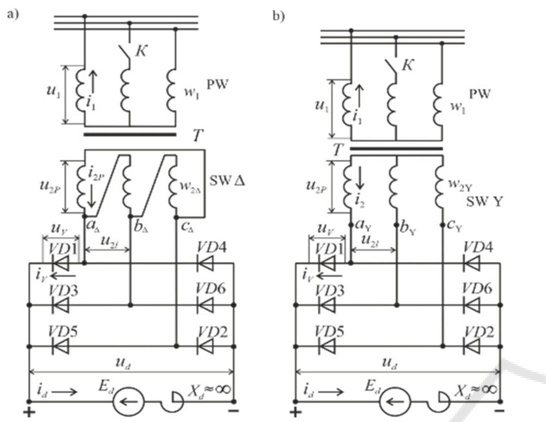

Figure 1: Schematics of 6Y/Δ (a) and 6Y/Y (b) rectifiers.

When the K key is closed (Figures 1, a and b), the circuits operate in all-phase mode. The vector diagrams of the phase and line voltages of their secondary windings for this mode are shown in Figures 2, a and b respectively. The rectified voltages 6Y/Δ and 6Y/Y are generated by the apex line voltages of the transformer secondary windings and have six fluctuations per supply period (Wang, 2018).

In full-phase mode of these converters, the relations between voltages, currents and powers are determined by the known expressions (Worku, 2018), which are given in Table 1. In the same table similar relations for two-pulse bridge rectification scheme (2B) are given (Worku, 2018).

Table 1 indicates:

U2L, U2PH — effective values of line and phase voltages of transformer secondary windings;

Ud0, Id — average values of no-load voltage and rectifier current;

IV — average current of the rectifier's valve arm;

UV MAX — maximum reverse voltage of the rectifier valve arm;

I2PH, I1PH — effective values of phase currents

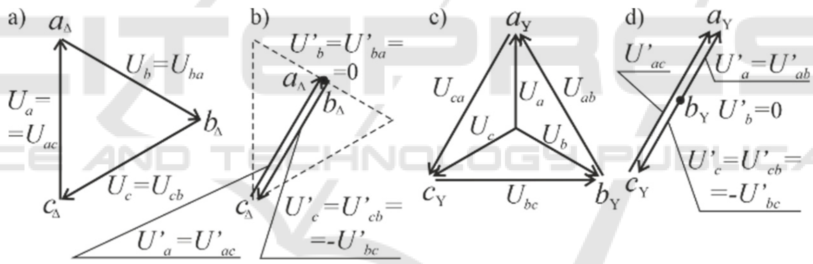

Figure 2: Vector diagrams of secondary winding voltages 6Y/Δ (a, b) and 6Y/Y (c, d) full-phase (a, c) and single-phase (b, d) modes.

Table 1: Relationship between voltages, currents and powers of six-pulse (6Y/Δ, 6Y/Y) and two-pulse bridge (2B) rectifiers in full-phase mode with different secondary winding arrangements.

Parameter	6M Y/Δ		6M Y/Y		2B	
$\frac{U_{2L}}{U_{2PH}}$	1	(1)	$\sqrt{3} = 1.732$	(8)	1	(15)
$\frac{U_{d0}}{U_{2PH}}$	$\frac{3\sqrt{2}}{\pi} = 1.35$	(2)	$\frac{3\sqrt{6}}{\pi} = 2.339$	(9)	$\frac{2\sqrt{2}}{\pi} = 0.9003$	(16)
$\frac{I_V}{I_d}$	$\frac{1}{3} = 0.3333$	(3)	$\frac{1}{3} = 0.3333$	(10)	$\frac{1}{2} = 0.5$	(17)
$\frac{U_{V\,MAX}}{U_{2PH}}$	$\sqrt{2} = 1.414$	(4)	$\sqrt{6} = 2.449$	(11)	$\sqrt{2} = 1.414$	(18)
$\frac{I_{2PH}}{I_d}$	$\frac{\sqrt{2}}{3} = 0.4714$	(5)	$\sqrt{\frac{2}{3}} = 0.8165$	(12)	1	(19)
$\frac{I_{1PH} \cdot k_T}{I_d}$	$\frac{\sqrt{2}}{3} = 0.4714$	(6)	$\sqrt{\frac{2}{3}} = 0.8165$	(13)	1	(20)
$\frac{S_{2H}}{P_{d0}} = \frac{S_{1H}}{P_{d0}}$	$\frac{\pi}{3} = 1.047$	(7)	$\frac{\pi}{3} = 1.047$	(14)	$\frac{\pi}{2\sqrt{2}} = 1.111$	(21)

of transformer secondary and primary windings;

$k_T = \frac{w_1}{w_2}$ — transformation ratio;

w1, w2 — number of turns of primary and secondary windings of the transformer;

S2H, S1H — rated power ratings of transformer secondary and primary windings;

S2H = 3·U2H·I2H, S1H = 3·U1H·I1H — rated power ratings of transformer secondary and primary windings;

Pd0 = Ud0 IdH·— notional rated power at the rectifier output.

3 RESULTS AND DISCUSSION

We will consider the operation of 6Y/Δ when the connection between mains and phase B is open, i.e., when the key K in figure 1, a is open.

In this case, the circuit will switch to an incomplete phase mode. Phase voltages and currents B and bΔ are equal to zero. Only the phases A, C, aΔ and cΔ are involved.

The vector diagrams of the phase and line voltages of the secondary 6Y/Δ open phase transformer are shown in Figure 2, b. From this figure it can be seen that the phase voltages aD and cD (U'a and U'c), and linear (U'ac and U'cb) are reduced cos π/3 times, and modulo become equal to each other:

$$U'_a = U'_{ac} = -U'_c = -U'_{cb} = U'_{bc} = U_{2L} \cdot cos\frac{\pi}{3} = \frac{\sqrt{3}}{2} U_{2PH}. \quad (22)$$

Thus, the six-pulse rectifier circuit of the inverter in question is converted into a two-pulse bridge circuit when the B phase circuit is interrupted. As a single-phase secondary voltage, two phase voltages of equal magnitude and direction are connected in parallel (u'a and -u'c) or linear (u'ac and u'bc) voltages, of those phases which are not in phase mode. In the case of a disconnection in phase A, these will be u'ab and u'cb, and in the phase C these will be u'ac and u'ab.

Since the break occurs in phase B, there will be voltages applied to the rectifier u'ac and u'bc, the amplitudes of which are $\sqrt{3}/2$ less than the amplitudes of the voltages uac and ubc of the full-phase mode (Figure 2, b).

At the interval where the highest potential at the point aΔ and bΔ, and the smallest at the point cΔ (Figure 3, a), the current flows as follows. The first half of the load current flows out of the point aΔ, and the second from the point bΔ. Running through VD1 and VD3 respectively, these currents are connected at the common cathode of the rectifier, and then through the load circuit and VD2. They then branch out again at the point cΔ, passing through the phases aΔ and cΔ. Voltage is applied to the load u'ac(bc) (Figure 2, b), and the rectifier operates VD1, VD3 and VD2 (Figure 3, a).

At the interval where the highest potential at the point cΔ, and the lowest – at the point aΔ and bΔ. (Figure3, b), the load current flows through the circuit: point cΔ, VD5, load. The current then splits - the first half flows through the VD4 circuit, point aΔ, phase aΔ, point cΔ, and the second by the circuit VD6, point bΔ, phase cΔ, point cΔ. Voltage u'ca(cb) is applied to the load (Figure 2, b), and VD5, VD4 and VD6 operate in the rectifier (Figure 3, b).

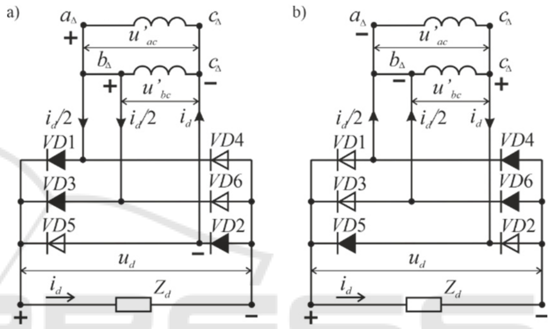

Figure 3: Instantaneous 6Y/Δ operation diagrams in an open phase mode.

Since 6Y/Δ operates as a two-pulse rectifier in partial phase mode, its average rectified voltage can be found from the expression (16). Therefore, according to (22), (1) and (2), we obtain:

$$U'_{d0} = \frac{2\sqrt{2}}{\pi} \cdot U'_2 = \frac{2\sqrt{2}}{\pi} \cdot U_{2PH} \cdot \frac{\sqrt{3}}{2} = \frac{\sqrt{6}}{\pi} \cdot U_{2PH} = \frac{1}{\sqrt{3}} \cdot U_{d0}. \quad (23)$$

It follows from (23) that the rectified voltage 6Y/Δ is reduced by a factor of 1.732 when there is an open circuit in any phase of the primary winding.

If the inverter operates according to Algorithm 1 (Zd = const), then the rectified current is reduced by the same amount and the power delivered to the load is reduced by a factor of 3:

$$I'_{d(A1)} = \frac{1}{\sqrt{3}} \cdot I_d, \quad (24)$$

$$P'_{d(A1)} = U'_{d0} \cdot I'_{d(A1)} = \frac{1}{\sqrt{3}} \cdot U_{d0} \cdot \frac{1}{\sqrt{3}} \cdot I_d = \frac{1}{3} \cdot P_d. \quad (25)$$

If the inverter operates according to Algorithm 2 (Pd = const), then the rectified current 6Y/Δ in partial phase mode must increase as much as the voltage has decreased, i.e., 1.732 times

$$I'_{d(A2)} = \sqrt{3} \cdot I_d. \quad (26)$$

Figure 3 shows that the currents of the diodes differ from each other when 6Y/Δ is operating in an open phase mode. In the example we are considering, the currents of VD2 and VD5 are twice the currents of VD1, VD3, VD4, VD6. Therefore, according to (17), we can write that the average current value of VD2 during 6Y/Δ operation in an open phase mode will be equal for Algorithm 1, considering (24) and (3), and for Algorithm 2, considering (26) and (10),

$$I'_{V(A1)} = \frac{1}{2\sqrt{3}} \cdot I_d = \frac{\sqrt{3}}{2} \cdot I_V; \qquad I'_{V(A2)} = \frac{\sqrt{3}}{2} \cdot I_d = \frac{3\sqrt{3}}{2} \cdot I_V. \quad (27)$$

In a two-pulse bridge rectifier circuit, the transformer secondary voltage (18) is applied to the diodes which are not in operation. Therefore, taking into account (18) and (4), we will write that the maximum reverse voltage of the valve arm 6Y/Δ in an open phase mode is:

$$U'_{V\,MAX} = \sqrt{2} \cdot U'_2 = \sqrt{2} \cdot U'_{2PH} = \sqrt{\frac{3}{2}} \cdot U_{2PH} = \frac{\sqrt{3}}{2} \cdot U_{V\,MAX}. \quad (28)$$

Figure 3 shows that when 6Y/Δ is operating in open phase mode, the phase currents aΔ and cΔ are the same and equal to half the id load current. On this basis, taking into account (19), it can be written that the effective value of the phase current aΔ 6Y/Δ in an open phase mode is equal to

$$I'_2 = \frac{1}{2} \cdot I'_d. \quad (29)$$

For Algorithm 1, considering (29), (24) and (5), and for Algorithm 2, considering (29), (26) and (5), we obtain:

$$I'_{2PH(A1)} = \frac{1}{2\sqrt{3}} \cdot I_d = \frac{\sqrt{3}}{2\sqrt{2}} \cdot I_{2PH}; \quad I'_{2PH(A2)} = \frac{\sqrt{3}}{2} \cdot I_d = \frac{3\sqrt{3}}{2\sqrt{2}} \cdot I_{2PH}. \quad (30)$$

Following a similar reasoning according to the expressions (20), (24), (26), (6) for the A phase current of the transformer's primary, we write:

$$I'_{1PH(A1)} = \frac{\sqrt{3}}{2\sqrt{2}} \cdot I_{1PH}; \; I'_{1PH(A2)} = \frac{3\sqrt{3}}{2\sqrt{2}} \cdot I_{1PH}. \quad (31)$$

Using the expressions (23)-(26), (30), (31), we find the calculated secondary and primary power ratings for 6Y/Δ open phase operation

$$S'_{2\text{H}(A1)} = S'_{1\text{H}(A1)} = 3 \cdot U_{2PH\text{H}} \cdot I'_{2PH\text{H}(A1)} = \frac{\pi}{2\sqrt{6}} \cdot P_{d0} = \frac{\sqrt{3}}{2\sqrt{2}} \cdot S_{2\text{H}}; \quad (32)$$

$$S'_{2\text{H}(A2)} = S'_{1\text{H}(A2)} = 3 \cdot U_{2PH\text{H}} \cdot I'_{2PH\text{H}(A2)} = \frac{\pi\sqrt{3}}{2\sqrt{2}} \cdot P_{d0} = \frac{3\sqrt{3}}{2\sqrt{2}} \cdot S_{2\text{H}}. \quad (33)$$

Now consider the operation of 6Y/Y when the key K is open (figure 1, b). In this case the voltages and currents of the phases B and bY are equal to zero. Only phases A, C, aY and cY are involved.

The vector diagrams of the phase and line voltages of the 6Y/Y open phase secondary winding are shown in Figure 2, d. It shows that the phase voltages aY and cY (U'a and U'c), as well as linear (U'ab and U'bc) decrease and modulo become equal to each other:

$$U'_a = U'_{ab} = -U'_c = -U'_{cb} = U'_{bc} = \frac{\sqrt{3}}{2} \cdot U_{2PH}.$$

However, the line voltage U'_{ac} remains unchanged

$$U'_{ac} = U'_a - U'_c = U_{ac} = U_{2L} = \sqrt{3} \cdot U_{2PH}.$$

This also converts the six-pulse rectifier circuit into a two-pulse bridge circuit in which the 6Y/Y line voltage of the phases which operate in partial phase mode acts as the single-phase secondary winding voltage. When the connection in phase B is disconnected it is Uac, when there is a phase A failure — Ubc, when there is a phase C failure — Uab.

In this case, the break occurs in phase B. Therefore, a voltage is applied to the rectifier u'ac, whose amplitude is equal to the amplitude of the full-phase line voltage.

At the interval where the highest potential at the point. aY, and the lowest – at the point. cY (Figure 4, a), the load current flows through the circuit: point aY, VD1, load Zd, VD2, point cY, phase cY, phase aY. Voltage u'ac is applied to the load (Figure 2, d), and VD1 and VD2 run in the rectifier (Figure 4, a).

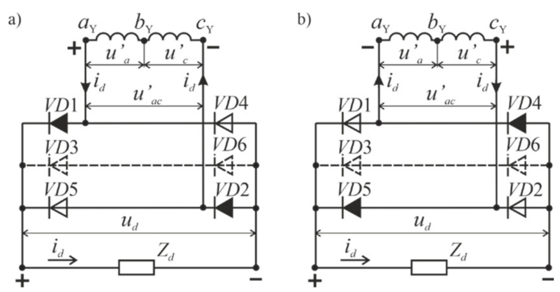

Figure 4: Instantaneous 6Y/Y open phase operation diagrams.

Table 2: Relationship between voltages, currents and powers of six-pulse rectifiers in single-phase operation with different secondary winding connection schemes.

Parameter	6M Y/Δ		6M Y/Y	
	Algorithm 1	Algorithm 2	Algorithm 1	Algorithm 2
$\frac{U'_{d0}}{U_{2PH}}$	$\frac{\sqrt{6}}{\pi}=0.7797$		$\frac{2\sqrt{6}}{\pi}=1.559$	
$\frac{U'_{d0}}{U_{d0}}$	$\frac{1}{\sqrt{3}}=0.5774$		$\frac{2}{3}=0.6667$	
$\frac{I'_d}{I_d}$	$\frac{1}{\sqrt{3}}=0.5774$	$\sqrt{3}=1.732$	$\frac{2}{3}=0.6667$	$\frac{3}{2}=1.5$
$\frac{P'_d}{P_d}$	$\frac{1}{3}=0.3333$	1	$\frac{4}{9}=0.4444$	1
$\frac{I'_V}{I'_d}$	$\frac{1}{2}=0.5$			
$\frac{I'_V}{I_d}$	$\frac{1}{2\sqrt{3}}=0.2887$	$\frac{\sqrt{3}}{2}=0.8660$	$\frac{1}{3}=0.3333$	$\frac{3}{4}=0.75$
$\frac{I'_V}{I_V}$	$\frac{\sqrt{3}}{2}=0.8660$	$\frac{3\sqrt{3}}{2}=2.598$	1	$\frac{9}{4}=2.25$
$\frac{U'_{V\,MAX}}{U_{V\,MAX}}$	$\frac{\sqrt{3}}{2}=0.866$		1	
$\frac{I'_{2PH}}{I'_d}$	$\frac{1}{2}=0.5$		1	
$\frac{I'_{2PH}}{I_d}$	$\frac{1}{2\sqrt{3}}=0.2887$	$\frac{\sqrt{3}}{2}=0.8660$	$\frac{2}{3}=0.6667$	$\frac{3}{2}=1.5$
$\frac{I'_{2PH}}{I_{2PH}}=\frac{I'_{1PH}}{I_{1PH}}$	$\frac{\sqrt{3}}{2\sqrt{2}}=0.6123$	$\frac{3\sqrt{3}}{2\sqrt{2}}=1.837$	$\sqrt{\frac{2}{3}}=0.8165$	$\frac{3\sqrt{3}}{2\sqrt{2}}=1.837$
$\frac{S'_{2H}}{P_{d0}}=\frac{S'_{1H}}{P_{d0}}$	$\frac{\pi}{2\sqrt{6}}=0.6413$	$\frac{\pi\sqrt{3}}{2\sqrt{2}}=1.924$	$\frac{\pi\sqrt{2}}{3\sqrt{3}}=0.855$	$\frac{\pi\sqrt{3}}{2\sqrt{2}}=1.924$
$\frac{S'_{2H}}{S_{2H}}=\frac{S'_{1H}}{S_{1H}}$	$\frac{\sqrt{3}}{2\sqrt{2}}=0.6123$	$\frac{3\sqrt{3}}{2\sqrt{2}}=1.837$	$\sqrt{\frac{2}{3}}=0.8165$	$\frac{3\sqrt{3}}{2\sqrt{2}}=1.837$

At the interval when the highest potential at the point cY, and the lowest – at the point aY (Figure 4, b), current flows through the circuit: point cY, VD5, load Zd, VD4, point aY, phase aY, phase cY. Voltage u'ca is applied to the load (Figure 2, b), and VD5 and VD4 run in the rectifier (Figure 4, b).

By carrying out the above listed considerations for 6Y/Δ and 6Y/Y (Figure 1, b), we can obtain the relations between voltages, currents and powers similar to the expressions (23) to (33), but for 6Y/Y.

The expressions for 6Y/Δ and 6Y/Y open phase with the results of their calculations are summarised in Table 2.

4 CONCLUSIONS

Thus, it can be stated that if any phase of the transformer primary is lost, the following processes occur in six-pulse rectifiers:

1) the rectifier circuits switch to a two-pulse mode;

2) the rectified voltages are reduced by a factor of 1.73 for 6Y/Δ and by a factor of 1.5 for 6Y/Y;

3) at unchanged load at the output of the rectifiers (Z_d = *const*), the output power drops by a factor of 3 for 6Y/Δ and 2.25 for 6Y/Y; all other values do not exceed the full-phase rating;

5) at the same power output of the rectifiers ($P_d = U_d \cdot I_d = const$), the valve arm currents increase by a factor of 2.6 for 6Y/Δ and 2.25 for 6Y/Y; the currents and power ratings of the secondary and primary windings increase by a factor of 1.84.

REFERENCES

Arzhannikov, B., Naboychenko, I., 2015. The concept of strengthening the traction power supply of direct current 3.0 kV: monograph. Yekaterinburg: USURT, p. 260.

Arzhannikov, B., 2019. Three-phase AC electric traction system: monograph. Yekaterinburg: USURT, p. 142.

Arzhannikov, B., 2019. Pat. No. 2688194 for the invention of IPC B60M 3/00, B60L 15/06. Traction power supply system for AC railways. No. 2018122747; declared 06/21/2018; publ. 21.05.2019, Bul. No. 15.

Belany, P., Novak, M., Siranec, M., Roch, M., Odelga, J., 2019. Design of a Filter Compensation Device for Traction Systems Support. *Transportation Research Procedia*. 40, pp. 136-143.

Chen, L., Chen, M., Chen, Y., Chen, Y., Cheng, Y., Zhaoc, N., 2021. Modelling and control of a novel AT-fed co-phase traction power supply system for electrified railway. *International Journal of Electrical Power & Energy Systems.* 125, p. 106405.

Fletcher, D., Harrison, R., Nallaperuma, S., 2020. TransEnergy – a tool for energy storage optimization, peak power and energy consumption reduction in DC electric railway systems. *Journal of Energy Storage.* 30, p. 101425.

Frey, Sh., 2012. Railway Electrification Systems & Engineering. First Edition, Published by: White Word Publications, p. 145.

Jefimowski, W., Szeląg, A., 2018. The multi-criteria optimization method for implementation of a regenerative inverter in a 3 kV DC traction system. *Electric Power Systems Research.* 161, pp. 61-73.

Kaudia, A., Barisala, A., Sahu, S., 2017. A Study of Various Traction Transformers & Active Power Compensator in Co-Phase Traction Systems. *Energy Procedia.* 117, pp. 252-259.

Ľuptáka, V., Stopkováa, M., Jurkovičb, M., 2020. Proposal for Introducing Uniform Traction Power System in Context of Efficient Locomotive Use. *Transportation Research Procedia.* 44, pp. 378-386.

Song, W., Jiangb, Z., Staines, M., Badcock, R., Wimbush, S., Fang, J., Zhang, J., 2020. Design of a single-phase 6.5 MVA/25 kV superconducting traction transformer for the Chinese Fuxing high-speed train. *International Journal of Electrical Power & Energy Systems.* 119, p. 105956.

Tlili, F., Kadri, A., Bacha, F., 2020. Advanced control strategy for bidirectional three phase AC/DC converter. *Electric Power Systems Research.* 179, p. 106078.

Yang, N., Pouget, J., Letrouvé, T., Jecu, C., Joseph-Augusteb, L., 2019. Techno-economic design methodology of hybrid energy systems connected to electrical grid: An application of hybrid railway power substation. *Mathematics and Computers in Simulation.* 158, pp. 107-119.

Wang, Q., Wu, J., Gao, J., Wang, J., Li, C., Wang, J., Zhou, N., 2018. Frequency-domain harmonic modeling and analysis for 12-pulse series-connected rectifier under unbalanced supply voltage. *Electric Power Systems Research.* 162, pp. 23-36.

Worku, G., Kebede, A., 2018. Autotransformer fed traction power supply system: analysis, modeling and simulation. *Global Energy Interconnection.* 1(2), pp. 187-196.