

A COMPREHENSIVE STUDY ON PERFORMANCE OF YD TRANSFORMER IN AC ELECTRIFIED RAILWAY SYSTEMS

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Abstract: *The selection of appropriate traction transformers decreases power quality problems and critical impacts of Electrified Railway System (ERS) on the power grid. Using the Yd transformer in ERSs is not common and popular like the power systems. In this paper, the performance of Yd transformer in a Traction Power Substation (TPS) is investigated and its superiority against single-phase, V/V and Scott transformer is ascertained. The evaluation and analysis is based on electrical performance, power quality parameters and economics issues. The analysis is studied under unbalanced and balanced conditions considering Railway Power Quality Compensator (RPQC) as the auxiliary compensator is TPS. The simulation results validate correctness of theoretical analysis.*

Key words: *Traction transformers, utilization parameters, railway power quality compensator, capacity reduction*

1. Introduction

Electrical railway systems are considered one of the main public transportation systems. These systems have power quality problems which can adversely affect other consumers and equipment in Point of Common Coupling (PCC) [1,2]. The large amount of Negative Sequence current (NSC), low Power Factor (PF) and undesirable harmonic currents are worth mentioning [3,4]. These problems cause adverse effects in utility power systems such as an increase in heat and loss in transformers and transmission lines, bad impact on protective systems and failure in performance of relays [5,6].

To limit aforementioned effects, different traction transformers like single-phase, V/V, Yd, Scott, Le-Blanc, Impedance-matching and Woodbridge have been used in all over the world [7,9]. For example, the single-phase connection is used in Italian, France and New-Zealand railways [10]. The V/V connection is used in France, British rail and Finnish state railways [10]. The Yd connection is used in China railway [10,11]. The Scott connection is used in Japanese Shinkansen and China [10,12]. The Le-Blanc connection is used in Taiwan railway and finally the Modified-Woodbridge connection is used in Japan and China [10,13,14]. Mainly, traction transformers are selected based on costs, physical profile of network and electrical performance. Using of these transformers is not enough to solve the power quality

problems of Traction Systems (TS), because they are unable to fully compensate aforementioned problems [15,16]. So, in the past researches they were compared without considering an auxiliary compensator in TS. After years, Railway Power Quality Compensator system (RPQC) was proposed in Japan as a comprehensive compensation device in TS [17]. This system is comprised of two back-to-back converters and it can compensate NSC, harmonics and reactive power simultaneously. However, after compensating in TPS, power quality parameters and other important factors like Transformer Utilization Factor (TUF), Line Utilization Factor (LUF) and the Current Unbalanced Ratio (CUR) will be changed for TS transformers.

In this paper, TS transformers and their performance have been evaluated based on power quality parameters and utilization factors specially CUR considering RPQC as a compensator in TPS. The evaluation results may provide significant guidance for TS transformer selection in the future.

This paper is organized as follows. In section 2, the popular TS transformers are introduced and their characteristics and structures have been summarized. In section 3, the CUR criteria of transformers, have been studied in details for both conditions of before compensation (without RPQC) and after compensation (with RPQC). Section 4 describes the configuration and operation principles of RPQC. In section 5, simulation results and analysis are presented and compared and finally, section 6 concludes this paper.

2. Popular TPS transformers

Different types of TPS transformers (i.e. single-phase, V/V, Yd) are used in electrical railway systems to improve power quality problems. The main task of these transformers is to convert a symmetrical three-phase voltage to a single phase voltage supplying traction load.

2.1. Single-phase connection

In single-phase connection, the primary side of the transformer is placed between the two phases, while the secondary side connects to the OCS and rail. All overhead lines connected to the TPS fed by the same phases. The configuration of this connection is shown

in Fig. 1. This transformer is simpler and cheaper than other kinds because of its structure [18,19].

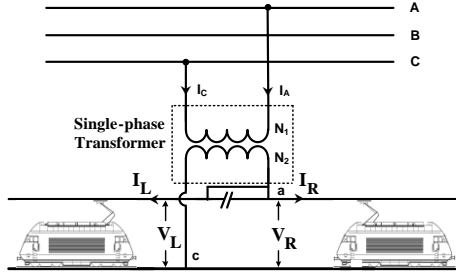


Fig. 1. Configuration of single-phase transformer in TPS

2.2. V/V connection

Fig. 2 indicates the structure of V/V transformer. It is comprised of two single-phase transformers with a common connection point between them. This connection is simpler than the others three phase transformers. As the weakness of this connection, it can be pointed to the failure in working when one of its phases ruins. In this connection, the overhead lines in two adjacent section fed by different phases. The V/V transformer is more expensive than single-phase transformers in the same power level of system [18,20].

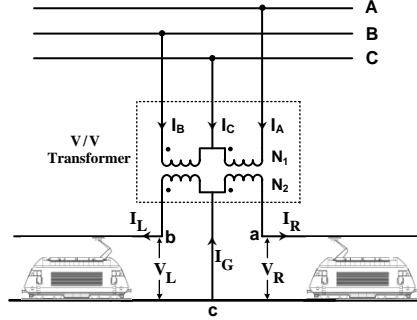


Fig. 2. Configuration of V/V transformer in TPS

2.3. Yd connection

The Yd connection transformers consist of different vector groups. Fig. 3 shows the configuration of the Yd11 connection in TPS. The Yd connection is more popular in China, Russia and Eastern Europe.

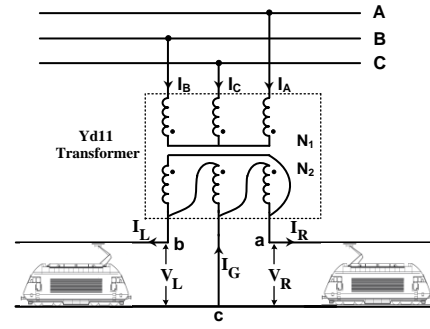


Fig. 3. Configuration of Yd11 transformer in TPS

As V/V connection, the overhead lines in two adjacent section fed by different phases.

The structural similarity of this transformer with transformers used in power transmission networks is the main advantages of this connection that can reduce the cost of utilizing and manufacturing. However, this connection is not popular in traction industry [11,18].

2.4. Scott connection

The Scott transformer is known as a balanced transformer which converts symmetrical three-phase voltage to two single phase voltages with 90 degree angle between them. This connection is popular in Japanese High Speed Railway (HSR). Figure 4 shows the electrical circuits of this type of connection. Due to the complex structure, this transformer is expensive [10,17].

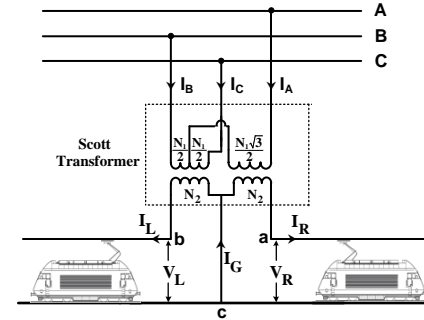


Fig. 4. Configuration of Scott transformer in TPS

Table.1 Technical comparison of TS transformers

Compared item	Single-phase	V/V	Yd	Scott
Structure	Simple	Relatively simple	Relatively simple	Complex
Utilization cost	High	High	Low	High
RPQC working capability	✗	✓	✓	✓
The compensation reactive power required	More	More	More	Less
The compensation NSC required	More	More	More	Less
The manufacturing cost	Less	Relatively less	Relatively less	High
Areas of application	Light loads	Relatively heavy loads	Relatively heavy loads	High speed railways

2.5. Technical comparison

Traction transformers are special power transformers which work in 100% overload condition. Due to the different structures of these transformers, they are evaluated by many technical factors. The comparison on technical performance of TS transformers is illustrated in Table I. In terms of internal structure the single-phase transformer is simple and V/V and Yd are relatively simple while the Scott transformer is a special, complicated and costly transformer which is not very commercial in traction systems and usually used in High Speed Railways (HSR). The manufacturing cost of this transformer is higher than others too [18,22].

As mentioned in Table 1, the RPQC can't compensate NSC in TPS with single-phase transformers, because they use just one phase and power transferring between two adjacent sections does not balance the primary side. Moreover, the amount of active and reactive power which should be transferred between two adjacent sections by RPQC is different in TS transformers. The balanced transformers like Scott have lower require for compensation of reactive power and NSC. In three-phase unbalanced transformers like V/V and Yd, the amount of reactive power and NSC compensation is higher.

3. Evaluation of TS transformers based on current unbalanced ratio parameter

To reduce the RPQC capacity through compensating harmonics and reactive power, the auxiliary compensators (i.e. passive and active filters, SVC, STATCOM) can be used. However, the impacts of TS transformers on RPQC capacity are based on NSC compensation.

In this section, the evaluation and analysis of TS transformers is carried out based on CUR index and the RPQC capacity. These factors are affiliated to load balance ratio, expressed as:

$$\zeta_l = \frac{|I_{load-left\ section}|}{|I_{Full\ load-left\ section}|} \quad (1)$$

$$\zeta_r = \frac{|I_{load-right\ section}|}{|I_{Full\ load-right\ section}|} \quad (2)$$

$$\zeta = \frac{|I_{light\ loaded\ section}|}{|I_{heavy\ loaded\ section}|} \quad (3)$$

ζ_l and ζ_r are the load balance ratio of left and right section of TPS. The value of ζ is between 0 and 1, and due to the fast dynamicity of traction loads it is always changing.

3.1. Current unbalance ratio

In AC electrical railway systems, traction loads are fed by single-phase voltages and currents in both sections of TPS. Therefore, the significant amount of

the NSC will be generated which makes the power network unbalanced. The performances of TS transformers in unbalanced conditions are different because of their structure. They are evaluated based on the current unbalanced ratio defined as:

$$CUR = \frac{|I^-|}{|I^+|} \quad (4)$$

I^- denotes negative sequence current and I^+ is positive sequence current.

3.2 CUR calculation without RPQC in TPS

The results of CUR equations under unbalanced condition (before compensation by RPQC) based on the load balance ratio are calculated in equations (5) to (26). In order to calculate the CUR for single-phase transformer, the configuration of TPS is considered as illustrated in Fig. 5. The primary side phase voltages are considered as:

$$\begin{cases} \dot{V}_A = V e^{i0} \\ \dot{V}_B = V e^{i\frac{4\pi}{3}} \\ \dot{V}_C = V e^{i\frac{2\pi}{3}} \end{cases} \quad (5)$$

Therefore, line-to-line and section voltages on secondary side are:

$$\dot{V}_R = \dot{V}_L = \dot{V}_{ac} = \frac{\dot{V}_{AC}}{a} = \frac{\sqrt{3}}{a} V e^{-i\frac{\pi}{6}} \quad (6)$$

Where V is the effective value of phase voltage and a is the ratio of the transformer. Considering PF is close to 1, the current in each section can be calculated as:

$$\begin{cases} \dot{I}_R = \zeta_r \dot{I}_{ac} = \zeta_r I e^{-i\frac{\pi}{6}} \\ \dot{I}_L = \zeta_l \dot{I}_{ac} = \zeta_l I e^{-i\frac{\pi}{6}} \end{cases} \quad (7)$$

Where I is effective value of current in secondary side. According to transformer features, three phase currents of primary side are:

$$\begin{bmatrix} \dot{I}_A \\ \dot{I}_B \\ \dot{I}_C \end{bmatrix} = \frac{I}{a} \begin{bmatrix} (\zeta_l + \zeta_r) e^{-i\frac{\pi}{6}} \\ 0 \\ -(\zeta_l + \zeta_r) e^{-i\frac{\pi}{6}} \end{bmatrix} \quad (8)$$

Using the Fortescue matrix, the load balance ratio can be calculated as follows:

$$\begin{bmatrix} \dot{I}^0 \\ \dot{I}^+ \\ \dot{I}^- \end{bmatrix} = \frac{I}{3a} \begin{bmatrix} 0 \\ \sqrt{3}(\zeta_l + \zeta_r) \\ \sqrt{3}(\zeta_l + \zeta_r) e^{-i\frac{\pi}{3}} \end{bmatrix} \quad (9)$$

Thus, the CUR can be calculated as follows:

$$CUR_{\text{single-phase}} = \frac{|I^-|}{|I^+|} = 1 \quad (10)$$

In order to calculate the current unbalance ratio for V/V transformer, the secondary side, line-to-line voltages are considered as:

$$\begin{cases} \dot{V}_R = \dot{V}_{ac} = \frac{\dot{V}_{AC}}{a} = \frac{\sqrt{3}}{a} V e^{-i\frac{\pi}{6}} \\ \dot{V}_L = \dot{V}_{bc} = \frac{\dot{V}_{BC}}{a} = \frac{\sqrt{3}}{a} V e^{-i\frac{\pi}{2}} \end{cases} \quad (11)$$

Considering PF is close to 1, the current in each section can be calculated as:

$$\begin{cases} \dot{I}_R = \dot{I}_{ac} = \zeta_r I e^{-i\frac{\pi}{6}} \\ \dot{I}_L = \dot{I}_{bc} = \zeta_l I e^{-i\frac{\pi}{2}} \end{cases} \quad (12)$$

According to transformer features, three-phase currents of primary side are:

$$\begin{bmatrix} \dot{I}_A \\ \dot{I}_B \\ \dot{I}_C \end{bmatrix} = \frac{1}{a} \begin{bmatrix} \dot{I}_{ac} - \dot{I}_{ba} \\ \dot{I}_{bc} - \dot{I}_{ab} \\ \dot{I}_{ca} - \dot{I}_{bc} \end{bmatrix} = \frac{I}{a} \begin{bmatrix} \zeta_r e^{-i\frac{\pi}{6}} - 0 \\ \zeta_l e^{-i\frac{\pi}{2}} - 0 \\ -\zeta_r e^{-i\frac{\pi}{6}} - \zeta_l e^{-i\frac{\pi}{2}} \end{bmatrix} \quad (13)$$

Using the Fortescue matrix, the load balance ratio can be calculated as follows:

$$\begin{bmatrix} \dot{I}^0 \\ \dot{I}^+ \\ \dot{I}^- \end{bmatrix} = \frac{I}{3a} \begin{bmatrix} 0 \\ \sqrt{3}(\zeta_r + \zeta_l) \\ \sqrt{3}(\zeta_r e^{-i\frac{\pi}{3}} + \zeta_l e^{-i\pi}) \end{bmatrix} \quad (14)$$

Thus, the CUR can be calculated as follows:

$$CUR_{V/V} = \frac{|I^-|}{|I^+|} = \frac{\sqrt{\zeta_r^2 - \zeta_r \zeta_l + \zeta_l^2}}{\zeta_r + \zeta_l} \quad (15)$$

To calculate the CUR for Yd transformer, the secondary side, line-to-line voltages are considered as:

$$\begin{cases} \dot{V}_R = \dot{V}_{ac} = \frac{\dot{V}_{AC}}{a} = \frac{\sqrt{3}}{a} V e^{i0} \\ \dot{V}_L = \dot{V}_{bc} = \frac{\dot{V}_{BC}}{a} = \frac{\sqrt{3}}{a} V e^{-i\frac{\pi}{3}} \end{cases} \quad (16)$$

So, the current in each section can be calculated as:

$$\begin{cases} \dot{I}_R = \dot{I}_a = \zeta_r I e^{i0} \\ \dot{I}_L = \dot{I}_b = \zeta_l I e^{-i\frac{\pi}{3}} \\ \dot{I}_C = -(\dot{I}_a + \dot{I}_b) = -(\zeta_r I e^{i0} + \zeta_l I e^{-i\frac{\pi}{3}}) \end{cases} \quad (17)$$

According to Yd transformer features, the currents in

secondary side windings are:

$$\begin{bmatrix} \dot{I}_{ba} \\ \dot{I}_{cb} \\ \dot{I}_{ac} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ -1 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \dot{I}_a \\ \dot{I}_b \\ \dot{I}_c \end{bmatrix} \quad (18)$$

Thus, the current in primary side windings can be calculated as follows:

$$\begin{bmatrix} \dot{I}_A \\ \dot{I}_B \\ \dot{I}_C \end{bmatrix} = \frac{\sqrt{3}}{3a} \begin{bmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \times \begin{bmatrix} \dot{I}_{ab} \\ \dot{I}_{bc} \\ \dot{I}_{ca} \end{bmatrix} = \frac{\sqrt{3}}{3a} \begin{bmatrix} \zeta_l I e^{-i\frac{\pi}{3}} - \zeta_r I e^{i0} \\ -2\zeta_l I e^{-i\frac{\pi}{3}} - \zeta_r I e^{i0} \\ 2\zeta_r I e^{i0} + \zeta_l I e^{-i\frac{\pi}{3}} \end{bmatrix} \quad (19)$$

Using of Fortescue transformation, the current balance ratio can be calculated by following equations:

$$\begin{bmatrix} \dot{I}^0 \\ \dot{I}^+ \\ \dot{I}^- \end{bmatrix} = \frac{\sqrt{3}I}{3a} \begin{bmatrix} 0 \\ (\zeta_r + \zeta_l) e^{-i\frac{2\pi}{3}} \\ \zeta_r e^{i\frac{2\pi}{3}} + \zeta_l e^{i0} \end{bmatrix} \quad (20)$$

Thus, the CUR can be calculated as follows:

$$CUR_{Yd} = \frac{|I^-|}{|I^+|} = \frac{\sqrt{\zeta_r^2 - \zeta_r \zeta_l + \zeta_l^2}}{\zeta_r + \zeta_l} \quad (21)$$

The configuration of Scott transformer is illustrated in Fig. 5. Considering the primary side phase voltages as (5), line-to-line voltages on secondary side are:

$$\begin{cases} \dot{V}_R = \dot{V}_{ac} = \frac{\dot{V}_{AC}}{a} = \frac{\sqrt{3}}{a} V e^{i0} \\ \dot{V}_L = \dot{V}_{bc} = \frac{\dot{V}_{BC}}{a} = \frac{\sqrt{3}}{a} V e^{-i\frac{\pi}{2}} \end{cases} \quad (22)$$

Considering PF close to 1, the current in each section can be calculated as:

$$\begin{cases} \dot{I}_R = \dot{I}_{ac} = \zeta_r I e^{i0} \\ \dot{I}_L = \dot{I}_{bc} = \zeta_l I e^{-i\frac{\pi}{2}} \\ \dot{I}_G = -(\dot{I}_{ac} + \dot{I}_{bc}) = -(\zeta_r I e^{i0} + \zeta_l I e^{-i\frac{\pi}{2}}) \end{cases} \quad (23)$$

According to transformer features, three-phase currents of primary side are:

$$\begin{bmatrix} \dot{I}_A \\ \dot{I}_B \\ \dot{I}_C \end{bmatrix} = \frac{1}{a} \begin{bmatrix} \frac{2}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{3}} & 1 \\ -\frac{1}{\sqrt{3}} & -1 \end{bmatrix} \begin{bmatrix} \dot{I}_R \\ \dot{I}_L \end{bmatrix} = \frac{I}{a} \begin{bmatrix} \frac{2}{\sqrt{3}} \zeta_r e^{i0} \\ -\frac{1}{\sqrt{3}} \zeta_r e^{i0} + \zeta_l e^{-i\frac{\pi}{2}} \\ -\frac{1}{\sqrt{3}} \zeta_r e^{i0} - \zeta_l e^{-i\frac{\pi}{2}} \end{bmatrix} \quad (24)$$

Using of Fortescue transformation, the CUR can be calculated by following equations:

$$\begin{bmatrix} \dot{I}^0 \\ \dot{I}^+ \\ \dot{I}^- \end{bmatrix} = \frac{I}{3a} \begin{bmatrix} 0 \\ \sqrt{3}(\zeta_r + \zeta_l) \\ \sqrt{3}(\zeta_r - \zeta_l) \end{bmatrix} \quad (25)$$

Therefore, the CUR can be calculated as follows:

$$CUR_{\text{Scott}} = \frac{\dot{I}^-}{\dot{I}^+} = \frac{(\zeta_r - \zeta_l)}{(\zeta_r + \zeta_l)} \quad (26)$$

3.3 CUR calculation with RPQC in TPS

In balanced and ideal conditions (after full compensation by RPQC) the CUR in three phase transformers (V/V, Yd and Scott) should be decreased to near zero. However, the RPQC can't compensate NSC in TPS with single-phase transformers. Therefore, for the single-phase transformers the CUR will be the constant value of 1. This means that RPQC is not useful in TPSs with single-phase Transformers. The calculated results of CUR parameter are summarized in Table 2.

3.4 RPQC Capacity

Since the approximate cost of passive compensation device is cheaper than the active compensation device, various researches have been done on using of active compensator devices, combined with passive ones to reduce RPQC capacity [23,24]. But, these methods have weaknesses in compensation performance. The type of TPS transformers is the main factor in RPQC nominal capacity selection. The amount of active and reactive power which should be transferred between two adjacent sections by RPQC is different in TS transformers. The balanced transformers like Scott have lower require for compensation of reactive power and NSC. Therefore, in TPSs with Scott transformers the RPQCs should have lower capacity. In three-phase unbalanced transformers like V/V and Yd, the amount of reactive power and NSC compensation is higher and the RPQCs should have a higher capacity.

4. RPQC operation

The configuration of RPQC in a TPS is illustrated in Fig. 5. The 230 kV three-phase high-voltage is stepped-down into two 27.5 kV single-phase voltages, which are connected to the Overhead Contact System (OCS) of two sections. As it can be seen in this figure, the RPQC is comprised of two back-to-back converters with a common DC-link capacitor. The RPQC should carry out the compensation duty for all traction network load conditions continuously.

Table. 2 CUR value of traction transformers

TS Transformers	Single-phase	V/V	Yd
CUR before compensation	1	$\frac{\sqrt{\zeta_r^2 - \zeta_r \zeta_l + \zeta_l^2}}{\zeta_r + \zeta_l}$	$\frac{\sqrt{\zeta_r^2 - \zeta_r \zeta_l + \zeta_l^2}}{\zeta_r + \zeta_l}$
CUR after compensation	1	0	0

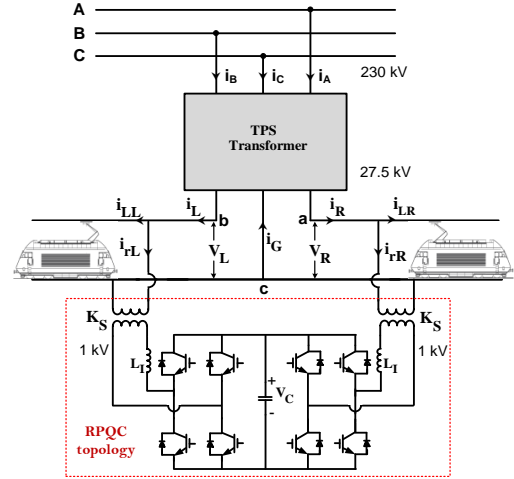


Fig. 5. TPS configuration with RPQC

So, it is considered that there are two traction locomotives in both sides of TPS. The load currents of right and left sections (i_{LR} and i_{LL}) are forwarded to the locomotives through the OCS and a pantograph to supply the power needs of traction motors. In order to compensate NSC, harmonic and reactive power simultaneously, the currents in the secondary side of TPS (i_R , i_L) should be completely sinusoidal, symmetrical and also in the same phase of their voltages (V_R , V_L).

5. Simulation Results

In order to verify the theoretical analysis, simulations based on MATLAB/SIMULINK software have been carried out. Since the low power factor and harmonic are substantial characteristic of railway systems, traction loads are modeled as an uncontrolled single-phase converter. As illustrated in Fig. 6, locomotive load is comprised of two uncontrolled half-bridge converters which are connected in series. The simulation parameters of system and traction load are shown in Table 3. As shown in Fig. 7, without RPQC, the single-phase transformer has the highest level of the CUR index (CUR=1) for all load, unbalanced ratios while the Scott transformer has the lowest level of CUR index. It is the best performance in comparison to the others. Meaning the rate of NSC injected to the three-phase system is lower in Scott transformer. The Yd and V/V transformers have the similar performance of CUR which is not as good as Scott transformers.

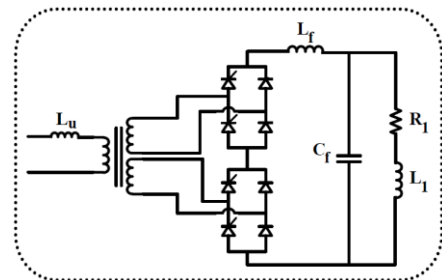


Fig. 6. Traction load model

Table. 3 Parameters of simulation system and traction load

Parameter	Value
TPS transformer ratio (K_T)	230:27.5
Step-down transformer ratio (K_S)	27.5:1
Interface inductance (L_I)	0.5 mH
DC-link capacitor (C)	40 mF
Traction load inductance (L_u)	9.2 mH
Traction load inductance (L_f)	240 mH
Traction load capacitor (C_f)	40 μ F
Traction load resistor (R_l)	120 Ω
Traction load inductance (L_l)	40 mH

In order to evaluate the impacts of the TS transformer type on RPQC performance and its capacity the proposed system is simulated for V/V, Yd11 and Scott transformers separately.

As represented in Fig. 8, before compensation the network-side three-phase currents are significantly unbalanced and asymmetrical. It can be seen from the simulation results illustrated in Tables IV and V that the CUR is about 55% and 99% for $\zeta = 0.5$ and $\zeta = 0$ respectively. After turning on of RPQC at $t = 0.1$ s, by transferring power between sections, the network-side three-phase currents became symmetrical and balanced. Thereupon, CUR is detracted to less than 3%.

Fig. 9 demonstrates the RPQC capacity. The power ratings of RPQC and its back-to-back converters depends on the amount of transferring and compensated active and reactive power. It is obvious from this figure that, for the Scott transformer the RPQC capacity is lower. It means that, the RPQC can be used with a lower nominal capacity of equipment. The figure also shows a minor superiority of the Yd transformer against V/V transformer.

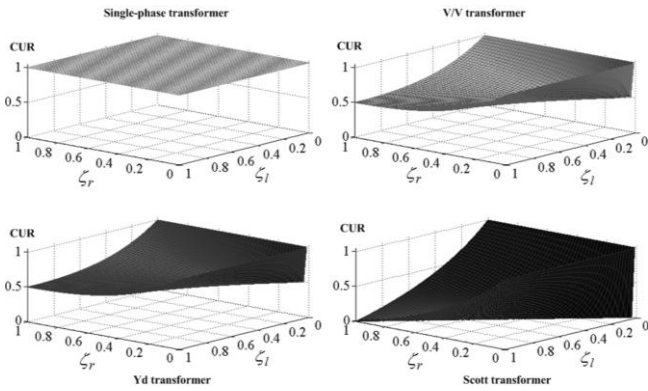
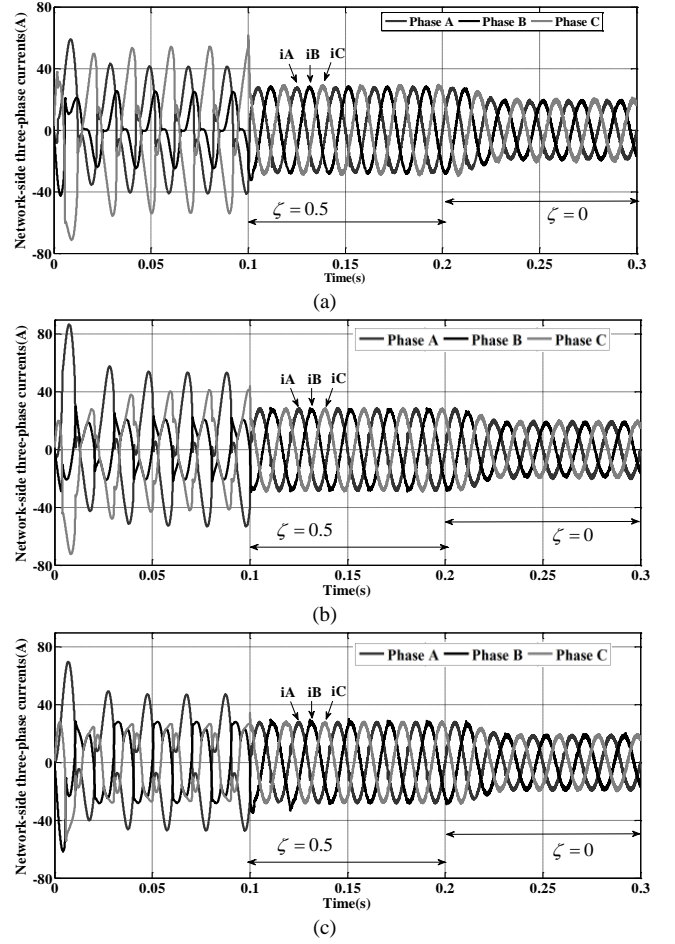
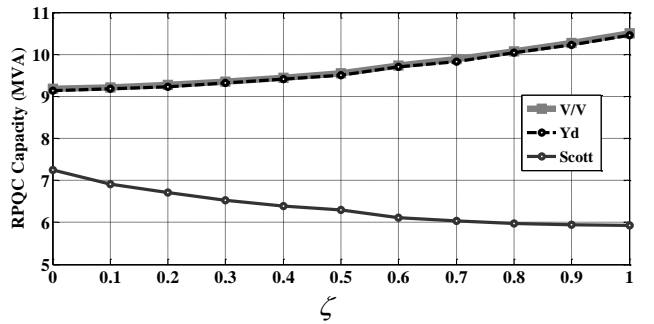
**Fig. 7.** CUR value without RPQC**Fig. 8.** Network-side three-phase currents for a) V/V transformer b) Yd transformer c) Scott transformer**Fig. 9.** RPQC capacity

Table. 4 CUR value of traction transformers

	Single-phase	V/V	Yd	Scott
CUR% before compensation	-	54.68	54.49	31.62
CUR% after compensation	-	1.61	0.7	0.41
RPQC Capacity (MVA)	-	9.547	9.510	6.292

Table. 5 CUR value of traction transformers

	Single-phase	V/V	Yd	Scott
CUR% before compensation	-	98.82	98.77	99.94
CUR% after compensation	-	2.43	1.19	0.63
RPQC Capacity (MVA)	-	9.177	9.135	7.244

6. Conclusion

In this paper, the performance of popular commercial TS transformers (Single-phase, V/V, Yd, Scott) investigated with the presence of RPQC as the auxiliary compensator in TPS. In the beginning, after a brief description about RPQC performance, the structures and connections of TS transformers are presented. Then, a technical comparison considering manufacturing and utilization costs, the compensation volume required and areas of application accomplished. Using the voltages and currents equations, the mathematical equations of CUR calculated considering various load unbalanced ratio. The equations calculated with and without RPQC separately. To validate the theoretical analysis, simulations carried out. The simulation results showed that in case without RPQC, the single-phase and Scott transformers have the highest and lowest level of CUR index respectively. The results show that RPQC capacity is lower for Scott transformer and also they illustrate a minor superiority of the Yd transformer against V/V transformer. It is demonstrated that unlike the past articles related to RPQC systems which three-phase V/V transformers were widely used in traction systems Yd transformers are more common, cheaper and popular in industry comparing to V/V transformers; as a result, due to the high cost of Scott transformers, the Yd transformer are a better choice to put into operation with RPQC in TPS.

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