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COST ESTIMATION OF RAIL POWER CONDITIONER TOPOLOGIES BASED ON INDIRECT MODULAR MULTILEVEL CONVERTER IN V/V AND SCOTT POWER TRANSFORMERS

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KEYWORDS

Rail Power Conditioner, Modular Multilevel Converter, V/V Transformer, Scott Transformer, Cost Estimation.

ABSTRACT

This paper presents a cost estimation study for several rail power conditioner (RPC) topologies based on an indirect modular multilevel converter (MMC), in which these topologies are combined with V/V or Scott power transformers. The RPC topologies under interest in this paper are: the RPC based on a full-bridge MMC (RPC based on MMC4), the RPC based on two-phase three-wire MMC (RPC based on MMC3), and the RPC based on a half-bridge MMC (RPC based on MMC2). These RPC systems operate at medium voltage levels in the interconnection to 25 kV-50 Hz catenary sections to solve power quality problems, such as the current harmonics and the negative sequence components (NSCs) of currents. Along the paper are described the V/V and the Scott power transformers, the RPC main architectures, and the estimated cost of implementation for each RPC topology considering V/V or Scott implementations. As main contribution, the presented results could help in the selection procedure of the RPC topology, giving the best economical solution according to the used power transformer (V/V or Scott).

I. INTRODUCTION

Electric high-speed trains are single-phase traction loads that cause power quality deterioration to the power grid. These power quality problems increase the power losses as well as the operating costs of the trains (Tanta et al. 2018). The power quality problems associated to the current harmonics and to the negative sequence components (NSCs) of currents produced by the electric locomotives have drawn much attention by researchers. The NSCs of currents, in some cases, can reach up to 50% of the positive sequence components (PSCs) of currents at the fundamental frequency, and in such situations, the power quality can be highly deteriorated. Therefore, a compensation system can bring many benefits for a better operation of the electric locomotives and the public power system.

Rail power conditioner (RPC) systems are used to overcome the locomotives effect on the public power system side, i.e., to maintain balanced currents without NSCs, high power factor close to unity and a low value of current harmonics (Luo et al. 2011). The first implemented proposal was based on an RPC of 60 kV, 20 MVA for the Tohoku Shinkansen railway in Japan, in 2004 (Uzuka et al. 2004). However, and over the last years, a dramatic change has taken place toward submodules-based topologies, in which, cascade strings of converter submodules behave as controllable voltage sources (Xu et al. 2016). Within the purpose of enhancing the voltage and current ratings of the traditional RPC based on two-level back-to-back converters presented in (Luo et al. 2011), several options in a modular manner were developed in the last decade, in which the Modular Multilevel Converter (MMC) is identified as a promising solution (Tanta et al. 2019). The RPC based on indirect MMC is an applicable solution for the medium voltage applications because of its modularity and flexibility, where the converter’s total power rating is divided equally between several inner two-level converter submodules. This type of solution has attracted the researchers, especially in the East Asia countries (Japan and China). This is because the power electronic switches can withstand the medium voltage levels, and the RPC can be connected to the traction power system without using step-down coupling transformers. Furthermore, due to the multilevel nature, the power switches can operate at a lower switching frequency, which effectively decreases the switching losses (Tanta et al. 2017).

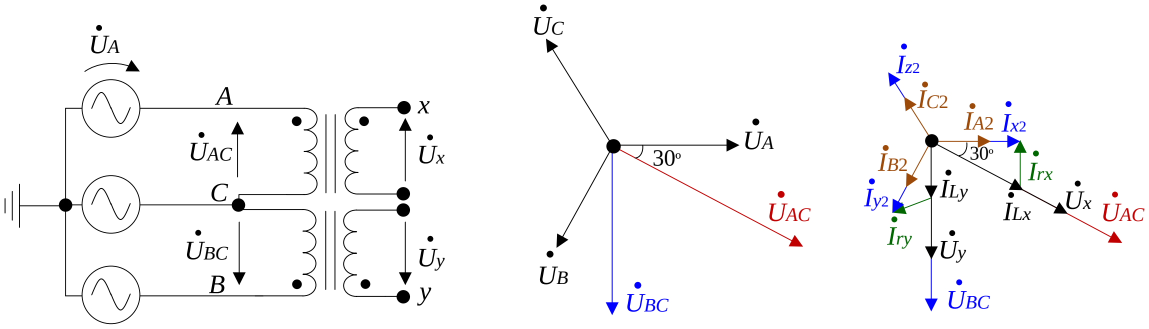
Three RPC topologies based on MMC are the main interest of this paper: the RPC based on a full-bridge MMC (RPC based on MMC4), the RPC based on two-phase three-wire MMC (RPC based on MMC3), and the RPC based on a half-bridge MMC (RPC based on MMC2). The cost of the aforementioned RPC topologies is not only related to the MMC parameters and elements, but also to the type of power transformer used (Xu et al. 2016), and therefore, this work will present a cost estimation study for these RPC topologies in the most common railway power transformers (V/V and Scott). There are different factors that determine the cost of each RPC topology, such as: the used traction power system (considering V/V or Scott transformers), the number of MMC submodules, the required passive elements for each RPC topology, power ratings of the power switches, the control complexity, and the system total volume. Simulation results of the RPC topologies are out of the scope of this paper but it can be found in (Xu et al. 2016) and (Song et al. 2016) for further information, and the study will focus on the cost analyzing. Within this framework, this paper is organized as follows: Section II describes the differences between the V/V and the Scott power transformers, Section III presents the RPC based on MMC topologies, Section IV provides a cost estimation study between the RPC topologies in V/V and Scott based power systems, and finally, Section V summarizes the final conclusions of the work.

II. V/V AND SCOTT POWER TRANSFORMERS

V/V transformers are widely used in the high-speed railway traction because of their simple structure, low cost and the high overload capacity comparing with the other transformer types such as the Scott or the LeBlanc transformer (Luo et al. 2011). It is very important to know when using a balanced transformer (e.g., Scott transformer), no NSCs of currents are injected into the public power grid when both load sections consume the same power (Pinto et al. 2018). However, when unbalanced V/V transformer is in use, the NSCs of currents injected to the public power system is half of the fundamental PSCs when both load sections consume the same power (Luo et al. 2011). Scott power transformer has more complex structure than the V/V power transformer. However, Scott transformer has several advantages in terms of power quality improvements. Normally, this transformer is used to perform the three-phase to two-phase conversion. It has a better performance to reduce NSCs of currents even when both of the catenary sections, loads (*x*) and (*y*), are unequally loaded (Abrahamsson et al. 2012).

Figure 1 (a) presents the V/V power transformer connection points to create two-phases for traction applications. Figure 1 (b) shows the phasors diagram of the primary windings. Figure 1 (c) shows the phasors diagram of the secondary windings. The load currents I_{Lx}, I_{Ly} are in phase with phase voltages U_x, U_y. The currents injected by the RPC are I_{rx}, I_{ry}. After compensation, V/V transformer primary windings currents are I_{A2}, I_{B2}, I_{C2} and the secondary windings currents after compensation are I_{x2}, I_{y2}, I_{z2}. The phase voltage U_x leads the phase voltage U_y by 60°. Figure 2 (a) presents the Scott power transformer connection points to create two-phases for traction applications. Figure 2 (b) shows the phasors diagram of the primary windings. The voltage U_{BC} is the line voltage and it leads the phase voltage U_B by 30°. The voltage U_{AD} is in phase with the phase voltage U_A. Figure 2(c) shows the phasors diagram of the secondary windings. In this case, the phase voltage U_x leads the phase voltage U_y by 90°. As a result of the aforementioned explanation, there is a phase difference of 60° between U_x and U_y in the V/V power transformer and a phase difference of 90° between U_x and U_y in the Scott power transformer.

Table 1 shows a brief comparison between the V/V and the Scott power transformers. V/V transformer has a simpler structure, a higher material utilization factor (a higher material utilization factor signifies a smaller transformer volume at the same nominal power) and lower manufacturing costs. However, a traction system with a V/V power transformer requires more reactive power and NSCs compensation comparing to a traction system with a Scott power transformer at the same load parameters (Xu et al. 2016). As a result, using the Scott power transformer could help to decrease the RPC compensation capacity.



(a) (b) (c)

Figure 1: V/V power transformer: (a) V/V transformer connection points; (b) Phasor diagram of the primary windings; (c) Phasor diagram of the secondary windings.

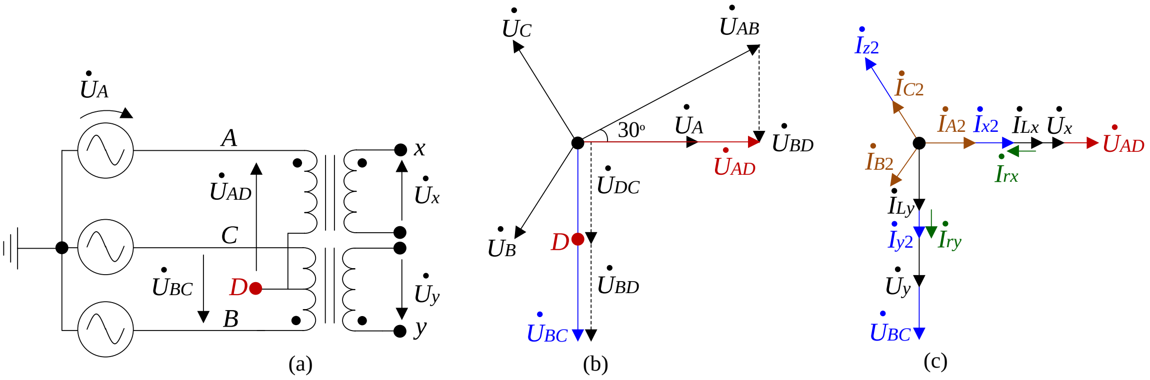


Figure 2: Scott power transformer: (a) Scott transformer connection points; (b) Phasor diagram of the primary windings; (c) Phasor diagram of the secondary windings.

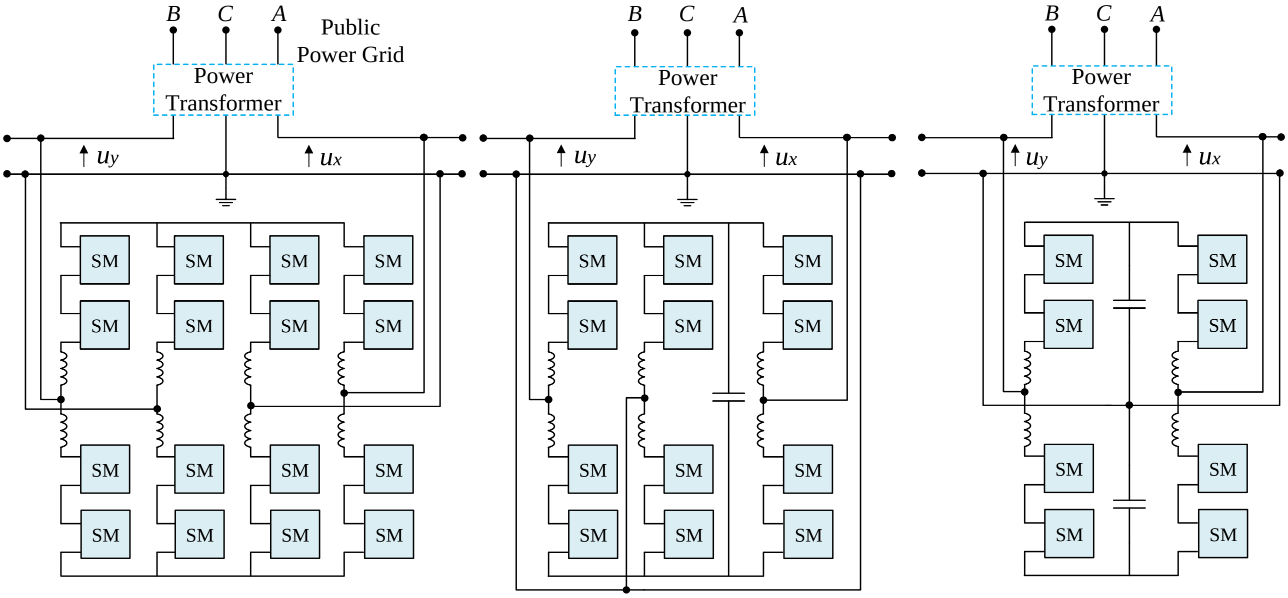
Table 1: Comparison between Scott and V/V transformers (Xu et al. 2015).

Compared Item	V/V Transformer	Scott Transformer
Structure	Simple	Complex
Material utilization factor	High (94%)	Low (81.6%)
Requirement for Reactive Power Compensation	More	Less
Requirement for NSCs Compensation	More	Less
Manufacturing Costs	Relatively less	High

III. RAIL POWER CONDITIONER TOPOLOGIES BASED ON INDIRECT MODULAR MULTILEVEL CONVERTER

Three RPC topologies under interest in this study are: the RPC based on MMC4, as shown in Figure 3 (a), the RPC based on MMC3, as shown in Figure 3 (b) and the RPC based on MMC2, as shown in Figure 3 (c). The RPC based on MMC4 consists of two back-to-back single-phase indirect MMC converters with half-bridge submodules. Each half-bridge submodule, as shown in Figure 4, contains two power switches (IGBTs) and one capacitor which could be inserted or bypassed (Tanta et al. 2019). The arm inductors are important to adjust the circulating current value between arms and to reduce the second order harmonic currents in the leg (Ronanki and Williamson 2018). The RPC based on MMC3 is quite different from the RPC based on MMC4 and it can be considered as a three-phase MMC operating to compensate the NSCs of currents under imbalance phase currents condition. Therefore, the phase to phase voltage ($U_{xy} = U_x - U_y$) magnitude is an important factor to be considered in the design parameters of the RPC based on MMC3. By another meaning, the DC-link voltage of RPC based on MMC3 should not be less than the peak magnitude of the phase-to-phase voltage (Xu et al. 2016). Since the RPC based on MMC3 does not have an implicit DC-link between the load sections converters as the case of RPC based on MMC4, it is recommended to add a DC-link capacitor between the legs converters to insure a good performance and to reduce the size of submodule capacitors as well. The RPC based on MMC2 could reduce the control complexity, costs, and the required hardware devices (Tanta et al. 2017). However, and in some scenarios, the costs of RPC based on MMC2 could be equal or exceed the costs of the RPC based on MMC3. Two DC-link capacitors are required to create a center-split midpoint for this solution.

The RPC based on MMC4 and the RPC based on MMC3 topologies have more reliability and robustness than the RPC based on MMC2 topology, where the failure of one power switch or one submodule will not strongly affect the MMC operation. On the contrary, if one of the main DC-link capacitors of the RPC based on MMC2 fails, this could harmfully affect all the converter operation. Each of the aforementioned RPCs can be either connected to the V/V or the Scott power transformers. As shown in Figure 3 (a), RPC based on MMC4 has the highest number of components, but this does not mean the indicated solution has the highest costs among the other RPC topologies. When the load sections are unequally loaded, the RPC should shift half of the active power difference from the highly loaded section to the lightly loaded section regardless the used type of power transformer (V/V or Scott). However, and in terms of reactive power compensation, the last is not a vital factor to be considered when using the RPC with the Scott power transformer (Xu et al. 2016) since the reactive power and the NSCs of currents have lower effects on the three-phase public power system when using the Scott power transformer.



(a) (b) (c)

Figure 3: Rail Power Conditioner (RPC) topologies based on indirect Modular Multilevel Converter (MMC): (a) RPC based on MMC4; (b) RPC based on MMC3; (c) RPC based on MMC2.

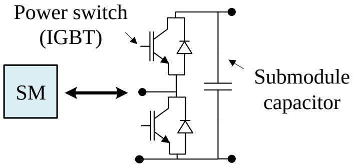


Figure 4: Indirect MMC submodule schematic (submodule equivalent circuit).

IV. COST ESTIMATION STUDY BETWEEN RAIL POWER CONDITIONER TOPOLOGIES

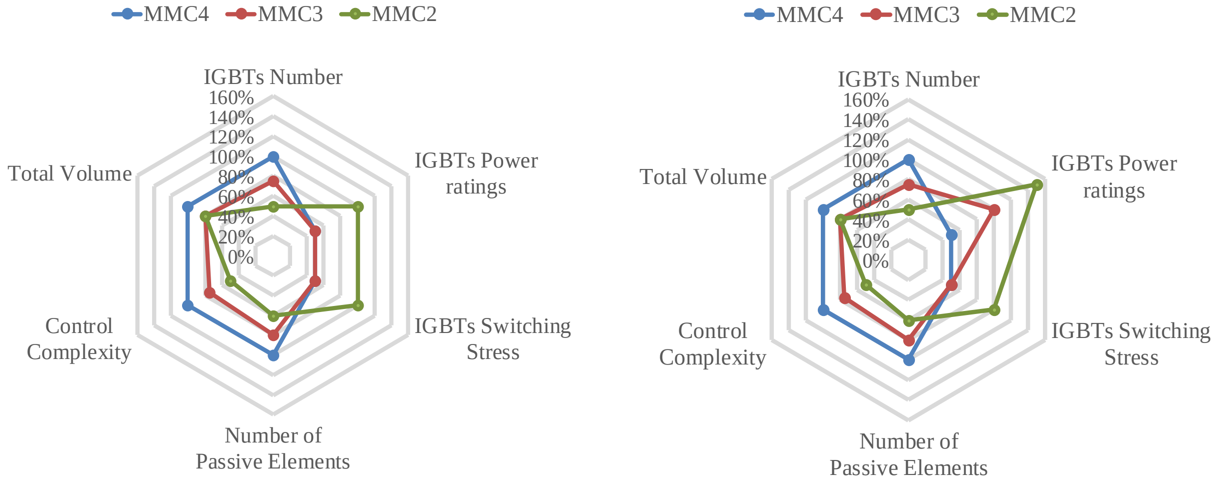
A technical and economical evaluation concerning the abovementioned RPCs, where a comparison was established in terms of hardware implementation estimated expenses, ignoring the final cost considering the industrialization process of the equipment. The abovementioned RPCs are compared when using the V/V power transformer, and then when using the Scott power transformer. The cost of RPC depends on the number of submodules, including the IGBTs voltage, current stress and other factors. According to Table 2, the RPC based on MMC4 has the highest number of power switches (IGBTs) and passive elements (capacitors and inductors) among all the topologies. All the studied RPCs have the same IGBT current stress, but the IGBT voltage stress is quite different. The highest required voltage stress is for the RPC based on MMC2 topology when using the Scott power transformer. Therefore, the estimated costs of single submodule for that topology is the highest as presented in Table 2. Moreover, this topology has a high IGBTs switching stress. By another meaning, the switching stress and the switching losses are twice in the RPC based on MMC2. The MMC main DC-link voltage should at least have a value equal to the peak amplitude of the phase-to-phase catenary sections voltages. This value is equal to $\sqrt{2}\,U_n$ (n belongs to x or y) in the RPC based on MMC4 regardless the used power transformer type. However, this value is bigger (2 U_n) in the RPC based on MMC3 when using the Scott power transformer. This is because of the 90° phase shift between U_x and U_y as shown in Figure 2(c). The phase-to-phase voltage in this case will have a value of $U_{xy} = \sqrt{2}\,U_x = \sqrt{2}\,U_y$. As a result and as presented in the estimated costs of the system in Table 2, the costs of the RPC based on MMC3 and of the RPC based on MMC2 could be higher when using the Scott power transformer than the case when using the V/V power transformer. As a consequence of a higher DC-link voltage in the RPC based on MMC3 and RPC based on MMC2, the power switches should withstand a higher voltage stress and a higher DC-link voltage value when using the Scott power transformer than the case when using the V/V power transformer, which sets additional isolation requirements and additional costs.

Figure 5 (a) presents a radar chart that compares the RPC based on MMC topologies when using the V/V power transformer. The RPC based on MMC4 has the highest number of elements and the highest control complexity among the compared RPC topologies, which make this solution an expensive one to be used in V/V power transformer ($\$*N$ as presented in Table 2, where N is the MMC output voltage level). The RPC based on MMC3 has fewer elements at the same IGBT power ratings and it demands a smaller area for installation, then the estimated costs of this solution are quite lower ($*0.79*N*). Also, the simulation results ensure the compensation performance of the RPC based on MMC3 is very similar to the RPC based on MMC4 when using the V/V power transformer (Xu et al. 2016). The RPC based on MMC2 and V/V power transformer could be a good solution in terms of reducing the total costs. However, the IGBT power ratings and the switching stress are double in this case, which could make this solution costly and bulky as long as the energy required for the locomotives is higher. The estimated costs of this solution ($$*0.58*N*) could exceed the ones of RPC based on MMC3 ($*0.79*N*), especially, at a heavy difference between the catenary lines load power.

Table 2: Comparison between the RPC topologies in V/V and Scott power transformers.

Parameters	V/V power transformer			Scott power transformer		
	RPC based on MMC4	RPC based on MMC3	RPC based on MMC2	RPC based on MMC4	RPC based on MMC3	RPC based on MMC2
IGBTs number	16*(*N*-1)	12*(*N*-1)	8*(*N*-1)	16*(*N*-1)	12*(*N*-1)	8*(*N*-1)
IGBT current stress	1 p.u.	1 p.u.	1 p.u.	1 p.u.	1 p.u.	1 p.u.
IGBT voltage stress	1 p.u.	1 p.u.	$\sqrt{2}$ p.u.	1 p.u.	$\sqrt{2}$ p.u.	2 p.u.
DC-link Voltage	$\geq \sqrt{2}\, U_n$	$\geq \sqrt{2}\, U_n$	$\geq 2\, U_n$	$\geq \sqrt{2}\, U_n$	$\geq 2\, U_n$	$\geq 2\sqrt{2}\, U_n$
Switching stress	f_{sw}	f_{sw}	$2\, f_{sw}$	f_{sw}	f_{sw}	$2\, f_{sw}$
Capacitors number	8*(*N*-1)	6*(*N*-1)+1	4*(*N*-1)+2	8*(*N*-1)	6*(*N*-1)+1	4*(*N*-1)+2
Estimated costs of single submodule	$	$	$$	$	$$	$$$
*Hardware factor (σ)	1	0.79	0.58	1	0.79	0.58
Estimated costs of the RPC based on MMC	$*N*	$*0.79*N*	$$*0.58*N*	$*N*	$$*0.79*N*	$$$*0.58*N*

N: MMC output voltage level; U_n: Output phase voltage of the RPC (U_x or U_y); f_{sw}: Switching frequency.
p.u.: per unit.
* Hardware factor (σ): This factor reflects the number of hardware devices and is calculated after considering the number of RPC based on MMC4 hardware devices as a reference, including passive elements (submodule capacitors, main DC-link capacitors, and coupled inductors) and number of IGBTs. This factor is calculated at the same MMC voltage level and power ratings, assuming the worst-case scenario when *N*=2.



(a) (b)

Figure 5: Comparison between RPC topologies based on indirect MMC when using: (a) V/V power transformer; (b) Scott power transformer.

Figure 5(b) presents a radar chart that compares the RPC based on MMC topologies when using the Scott power transformer. Although the RPC based on MMC4 requires more IGBTs and passive elements, this option is the preferable in this case. The RPC based on MMC3 DC-link voltage should at least meet the phase-to-phase voltage peak value. As a result, IGBTs with higher power ratings and bigger submodule capacitors are required. The previous reasons may lead to higher costs of the RPC based on MMC3 in Scott power transformer ($$*0.79*N*). These reasons are getting even worse in case of the RPC based on MMC2 ($$$*0.58*N*), where higher IGBTs power ratings are required. The area of each curve in Figure 5(a) and Figure 5(b) reflects the estimated costs of each RPC system.

V. CONCLUSION

This paper discussed a cost estimation study between different rail power conditioners (RPC) based on modular multilevel converter (MMC) topologies in V/V and Scott power transformers. The RPC topologies under interest were: RPC based on a full-bridge MMC (RPC based on MMC4), the RPC based on two-phase three-wire MMC (RPC based on MMC3), and the RPC based on a half-bridge MMC (RPC based on MMC2). The results confirm the RPC based on MMC3 is the preferred and the most economical solution when using the V/V power transformer with an estimated cost factor of ($*0.79*N*) as presented in Table 2. The performance of this solution is very similar to the RPC based on MMC4, but with a lower number of IGBTs, passive elements and with less control complexity. The RPC based on MMC2 can be a good and an economical solution to be used in the V/V power transformer at heavy traffic catenary lines. The study shows that the RPC based on MMC4 is the only suitable solution regarding the Scott power transformer. It is not recommended to use the RPC based on MMC3 or the RPC based on MMC2 when using the Scott power transformer. This is because the required power ratings of the power switches are higher, and this factor could increase the total costs of the RPC based on MMC3 and of the RPC based on MMC2. As a final conclusion, and after considering the recommendation of this paper, the RPC based on MMC3 in V/V power transformer has lower costs comparing to the RPC based on MMC4 in Scott power transformer. Then, using the V/V power transformer could help to relatively reduce the costs, especially, after knowing the manufacturing costs of such V/V transformer are relatively lower than the costs of the Scott power transformer.

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