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The effect of busbar shape and arrangement on currents and power losses in 3-phase busducts with two busbars per phase

***Abstract**. Several 3-phase busducts with two rectangular busbars per phase arranged in various ways were analyzed with respect to unequal current distribution and power losses. The effect of busbar shape was analyzed. Unshielded as well three types of shielded busducts were considered. The analysis results could be helpful in busduct design.*

***Streszczenie.** Przeanalizowano kilka trójfazowych torów prądowych z dwoma prostokątnymi szynoprzewodami na fazę pod kątem rozdziału prądów między szynoprzewody oraz strat mocy w nich. Badano wpływ kształtu i ułożenia szynoprzewodów Rozpatrywano tory nieekranowane, jak i trzy rodzaje ekranowania. Wyniki analizy mogą być pomocne w projektowaniu torów prądowych. (**Wpływ kształtu i ułożenia szynoprzewodów na prądy i straty mocy w trójfazowych torach prądowych z dwoma szynoprzewodami na fazę**)*

Keywords: three-phase busducts, rectangular busbars, unequal busbar load, busbar aspect ratio.
Słowa kluczowe: trójfazowe tory prądowe, szynoprzewody prostokątne, nierówne obciążenie szynoprzewodów, kształt szynoprzewodu.

Introduction

High current three-phase busducts sometimes have multiple busbars per phase (connected in parallel). Due to the phenomenon of electromagnetic induction resulting in the skin effect and the proximity effect, individual busbars are often unequally loaded [1]. This may lead to local overheating of the busduct due to high current density or to oversizing the busduct to avoid overheating. There is also an asymmetry in the matrix of self and mutual impedances and, as a result, the asymmetry of the currents even for symmetrical supply voltage and symmetrical receiver [1, 2]. The issue of equalizing currents in parallel lines is the subject of analysis of many researches (e.g. [3,4]). In this work, we analyzed several three-phase busducts with two rectangular busbars per phase to assess how various arrangements of busbars and their geometrical parameters affect the distribution of currents and power losses in individual busbars. We took into account unshielded busducts as well as their several shielded variants.

Analyzed busducts

Three-phase current busducts consisting of two rectangular busbars per phase were considered. Two base arrangements were taken into account. In the first one, the busbars are arranged in row (Fig. 1a); in the second – the busbars of each phase are arranged in stack, and the stacks are arranged in row (Fig. 1b). The cross-sectional dimensions of the busbars are $a \times b$ (see Fig. 1). The length of the busbars, l, is considered to be much larger than the cross-sectional dimensions of the busduct. The distance between busbars belonging to the same phase is d and the distance between neighboring busbars of adjacent phases is determined by c. It was assumed that busbars are made of copper (electrical conductivity γ_{Cu} = 58 MS/m), and the currents flowing through the busbars have a frequency f = 50 Hz and form a symmetrical 3-phase system of positive sequence. The busbars will be referred to as L*i*-*j*, where *i* - the phase number, *j* - the busbar number within the phase.

The busbars can be unshielded, but in most applications their shielded versions are used. Shielding makes the busduct a closed construction, which is safer and stronger, and reduces the magnetic field nearby the busduct. On the other hand, the currents induced in the shielding increase the power losses in the busduct and make it more expensive. Two types of shielding are considered in this paper: common shield for all phases (Fig. 2a) and individual shields for each phase (Fig. 2b). In the latter case, two main variants are possible – all shields connected at their ends or all completely shields separated. This gives four possibilities for each base arrangements of busbars: unshielded (US), with common shield (CS), individual connected shields (ICS) and individual isolated shields (IIS). In total, there are 8 configurations considered (Fig. 3). In the paper we assumed the shields are made of aluminum (γ_{Al} = 34 MS/m) and their thickness is g. The distance between the inner wall of the shield and the closest busbar wall was denoted by e.

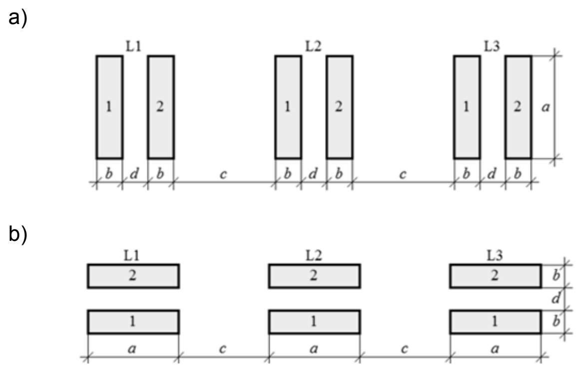

Fig.1. Base arrangements of analyzed busducts: a) row arrangement, b) stack-row arrangement

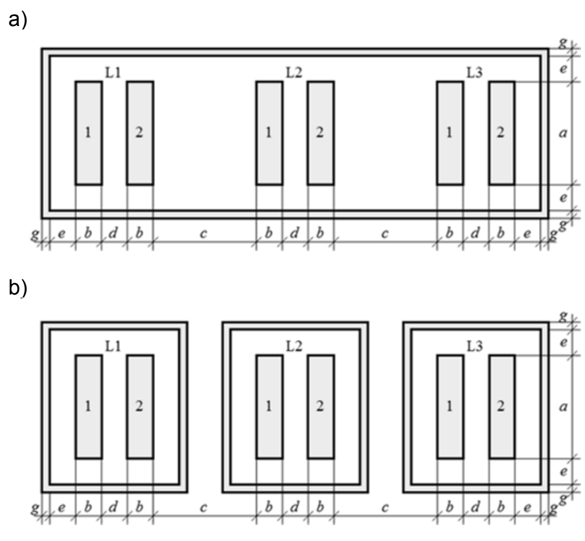

Fig.2. Common shield (a) and individual shields per phase (b)

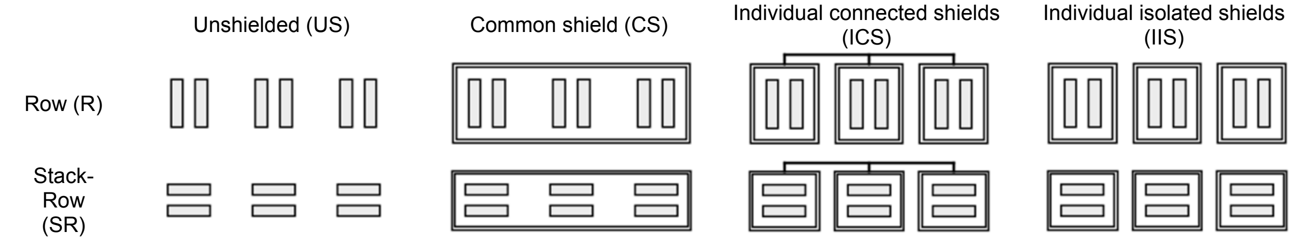

Fig.3. Considered busduct arrangements for 2 busbars per phase

Analyzed quantities

The analysis concerned the following aspects:

- how currents distribute throughout busbars and shields (if present),
- what are the power losses in each busbar and shield,
- where are the hot spots (points with highest current density),
- what is the effect of b/a ratio for constant ab,
- what is the effect of shielding type.

The analysis should be helpful in deciding which arrangement would be suitable for presumed aims.

To assess the current distribution throughout the busbars, the relative current in busbar L*i*-*j* was calculated as follows:

(1)
$$I'_{ij} = \frac{I_{ij}}{I}$$

where I_{ij} is the current in the busbar (RMS) and I is the phase current (RMS). In ideal case, I'_{ij} should be 1/n, where n is number of busbars per phase.

To asses the power losses in busbar L*i*-*j*, we introduced the relative power losses as follows:

(2)
$$P'_{ij} = \frac{P_{ij}}{I^2 R_{\mathrm{DC}}}, \qquad R_{\mathrm{DC}} = \frac{l}{\gamma_{\mathrm{Cu}} nab}$$

where P_{ij} is the power losses. P'_{ij} should be 1/n for equal load of busbars. The same formulas are used for shields.

To rate the unequal load of busbar, we introduce two indexes: unequality of currents index (UCI) and similar one for powers (UPI). They are defined as max to min ratio of respective values:

(3)
$$\mathrm{UCI} = \frac{I'_{\max}}{I'_{\min}}, \qquad \mathrm{UPI} = \frac{P'_{\max}}{P'_{\min}}$$

They should be 1 in ideal case.

The hot spots of each configurations where detected as follows. First, the point of the highest current density was found. Then additional characteristic points with current density not lower than 90% of the highest current density where found. To assess how ‘hot’ a point is, we determined the relative current density defined as follows:

(4)
$$J' = \frac{J}{I/(nab)}$$

Then J' informs how many times the current density exceeds the DC value.

To assess the effect of b/a ratio for other parameters given, we performed calculations for ratios 1/8, 1/4, 1/2, 1, 2, 4, 8 for constant cross-sectional area (ab = const). All calculations were performed with FEMM software (2D FEM) and in Wolfram Mathematica. The following values were used: number of busbars per phase n = 2, ab = 400 mm^2, c = 40 mm, d = e = 10 mm, g = 2 mm.

Analysis of currents in busbars

Figure 4 shows the maximal values of I'_{ij} for all the considered busducts. In row arrangements the maximal values of I'_{ij} are larger than in stack-row arrangements, in which the relative currents are equal to 0.5 due to symmetry. The highest values are for R-US (unshielded row arrangement). The smallest $I'_{ij\max}$ in row arrangement are mainly for ICS case. $I'_{ij\max}$ occurs usually in busbars L2-1 or L2-2, but sometimes L3-1 or L1-2, and never in side busbars.

	0.125	0.25	0.5	1.	2.	5.	8.
1	L2-1	L2-1	L2-1	L2-1	L2-1	L2-1	L2-1
2	L3-1	L3-1	L3-1	L2-2	L2-2	L2-2	L2-2
3	L3-1	L1-2	L1-2	L2-2	L2-2	L2-2	L2-2
4	L2-1	L2-1	L1-2	L1-2	L1-2	L1-2	L1-2

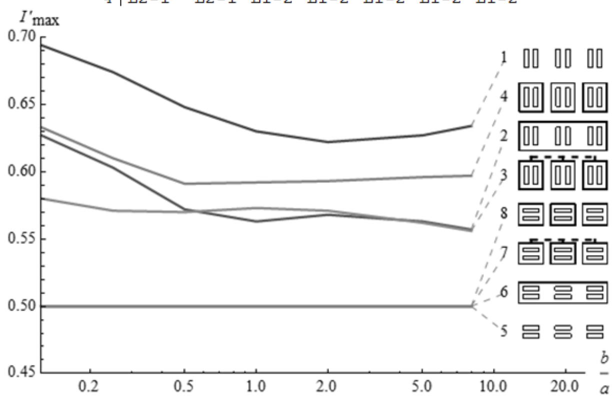

Fig.4. $I'_{ij\max}$ vs. b/a (parameters in text); the inset table in the upper part indicates busbars with the $I'_{ij\max}$

Figure 5 shows UCI for the considered busducts. It ranges up to 2, i.e. some busbars carry much larger currents than expected, what can lead to overheating or failures. The highest UCI occurs in R-US case for small b/a values. The SR case have UCI = 1 due to symmetry. Among R arrangements, the smallest UCI occurs for ICS case.

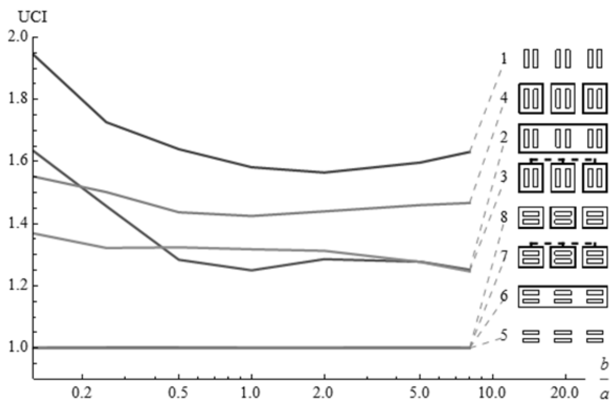

Fig.5. UCI vs. b/a (parameters in text)

Analysis of power losses

The P'_{max} in the busbars are depicted in Figure 6. The highest values are for R arrangement – they range approximately from 0.75 for ICS to 1 for US case. This does not mean that the total power losses are smallest in shielded busducts, because the presented values concern busbars, only. In SR arrangements, P'_{max} is usually smaller and decreases with an increase in b/a ratio. The inset table in Figure 5 indicates the busbars with the highest P'_{max}. In most cases this is L2-1, but sometimes L3-1, L2-2 or L1-2 appear. L1-1 and L6-2 (side busbars) never appear. In SR arrangements, P'_{max} occurs usually in L2-*j*, but sometimes in L3-*j*.

	0.125	0.25	0.5	1.	2.	5.	8.
1	L2-1	L2-1	L2-1	L2-1	L2-1	L2-1	L2-1
2	L3-1	L3-1	L3-1	L2-2	L2-2	L2-2	L2-2
3	L3-1	L1-2	L2-2	L2-2	L2-2	L2-2	L2-2
4	L2-1	L2-1	L1-2	L1-2	L1-2	L1-2	L1-2
5	L2	L2	L2	L2	L2	L2	L3
6	L2	L2	L2	L2	L2	L2	L2
7	L2	L2	L2	L2	L3	L3	L3
8	L2	L2	L2	L2	L2	L3	L3

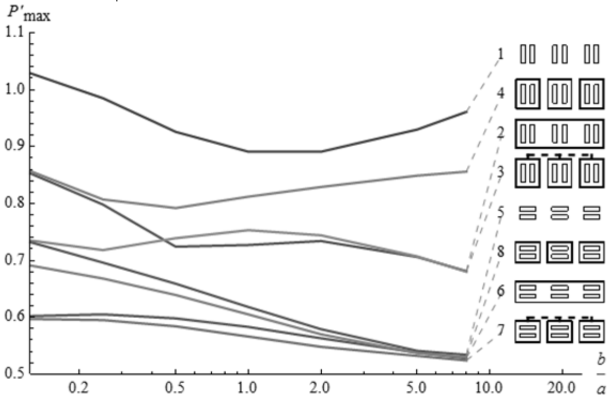

Fig.6. P'_{ijmax} vs. b/a (parameters in text); the inset table in the upper part indicates busbars with P'_{ijmax}

Figure 7 shows UPI for the considered cases. In R arrangements it is relatively large an reaches from 1.8 for ICS and CS cases to 3.5 for US case. Much smaller values, close to 1, occur for SR arrangements.

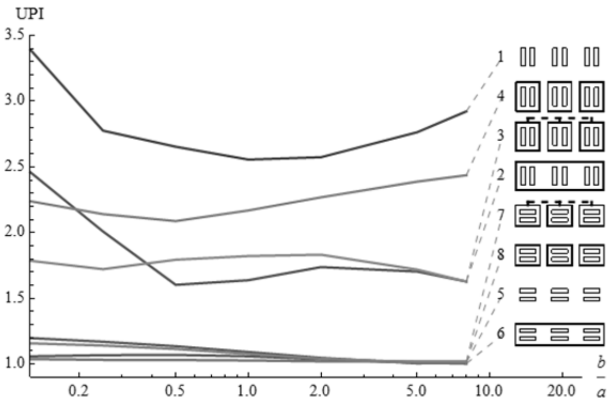

Fig.7. UPI vs. b/a (parameters in text)

Figure 8 shows the total relative power losses in each busduct. As expected, the highest power losses are usually in shielded busducts due to induced eddy currents in the shields. However, the RS-IIS case manifests relatively small power losses. In RS arrangements, the power losses decrease when b/a increases. In R arrangements, the trend is more complex.

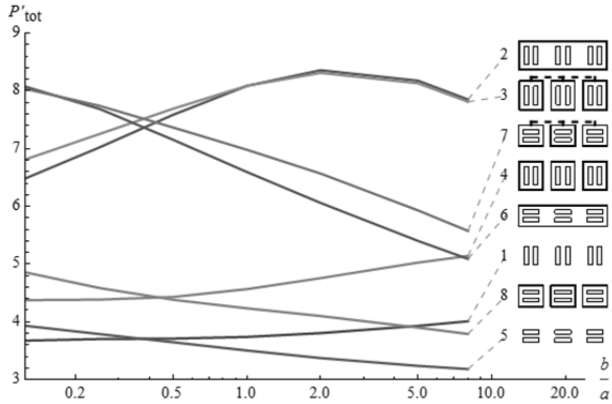

Fig.8. Total relative power losses in busduct vs. b/a (parameters in text)

Analysis of hot spots

Figure 9 shows J'_{max} (i.e. J' at the 'hottest' point). The values range from about 1.5 for RS arrangements and large b/a ratios to 2.6 for R-US at $b/a \approx 8$. The hot spots for each arrangement are presented in Figure 10. The position of the 'hottest' points, marked as ⊙, depend on busbar arrangement, shielding type and dimensions. For unshielded busducts, it usually belongs to L2-1, but shielding often changes it. CS and ICS cases have similar distribution of hot spots, whereas IIS cases manifest usually different hot spot distributions.

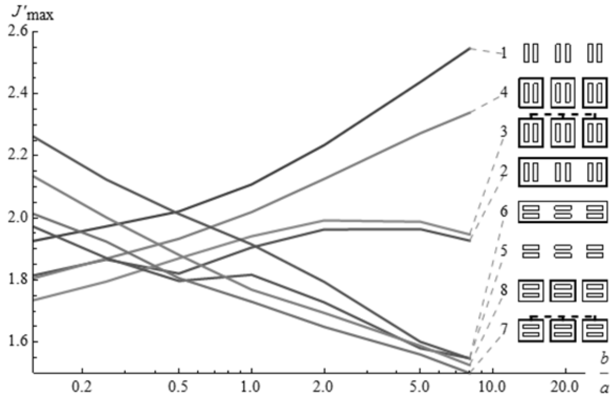

Fig.9. J'_{max} vs. b/a (parameters in text)

Conclusions

The presented analysis showed some characteristics of busducts with multiple rectangular busbars. The main conclusions are:

- busbars are sometimes loaded very unequally, currents in some busbars differ by a factor of 2 or larger,
- shielding type affects very much the characteristics,
- current density can locally reach values 2÷3 times larger than for DC case,
- properly selected aspect ratio b/a can improve busduct performance.

Some of the facts are commonly known to electrical engineers, but this detailed analysis can be helpful in deciding what arrangement of busbars to select in particular application. For example, it is worth observing that SR-IIS case with large b/a ratio has a relatively good performance: UCI = 1, UPI ≈ 1, small total power losses, and small J'_{max}. Of course, also other aspects must be taken into account. Besides, the analysis concerned only b/a ratio. It would be desirable to check the effect of other parameters, like shielding thickness or separation distances.

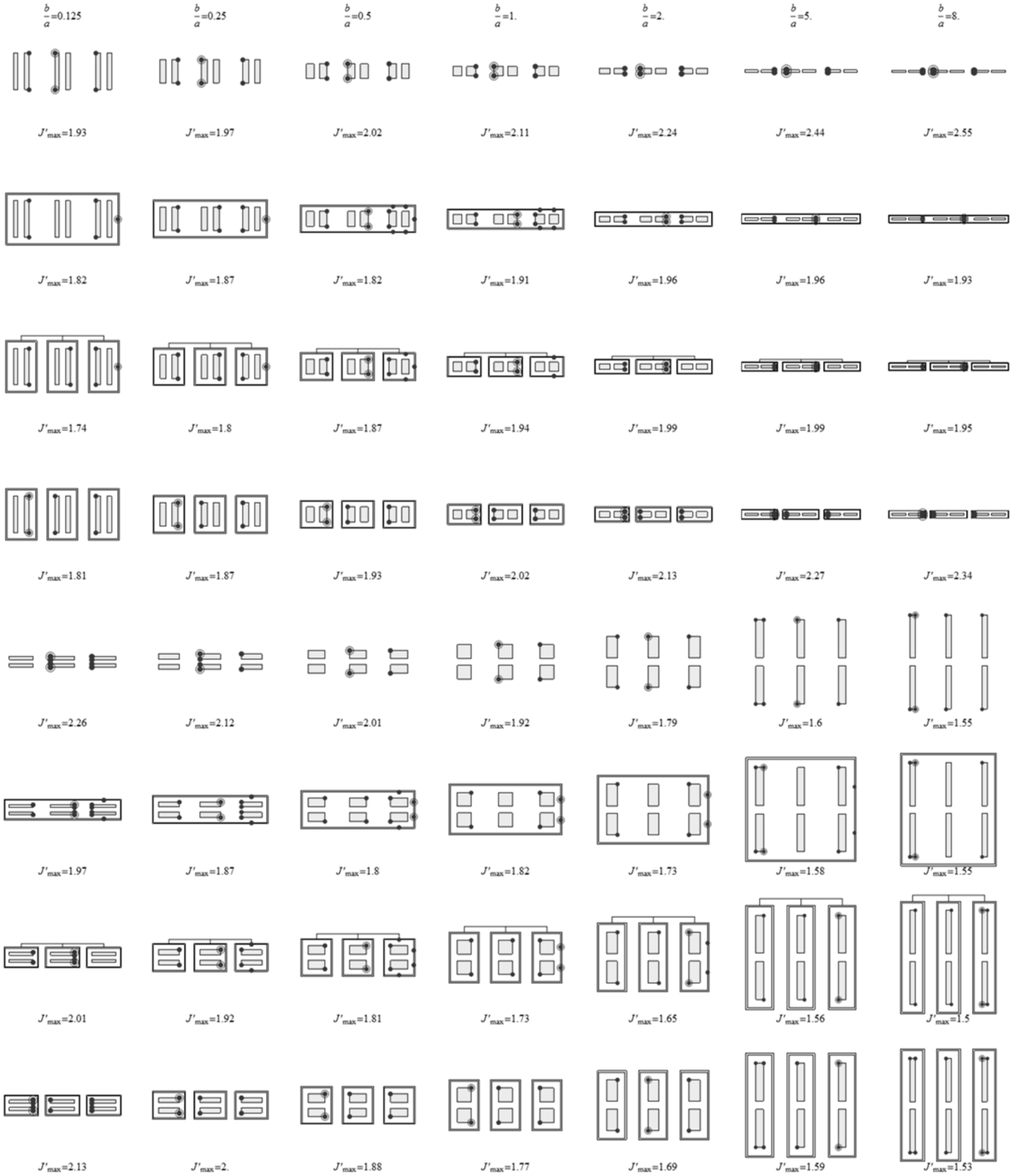

Fig.10. Hot spots in the considered busducts (in rows) and b/a ratios (in columns): (• - hot, ⊙ - the 'hottest'); parameters in text

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