



HERMITE-HADAMARD TYPE INEQUALITIES FOR HARMONICALLY CONVEX FUNCTIONS VIA KATUGAMPOLA FRACTIONAL INTEGRALS

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Received 25 October, 2018

Abstract. In this work, firstly, we established Hermite-Hadamard's inequalities for harmonically convex functions via Katugampola fractional integrals. Then we give some Hermite-Hadamard type inequalities of these classes functions.

2010 Mathematics Subject Classification: 26A33; 26A51; 26D10

Keywords: Hermite-Hadamard inequality, Riemann-Liouville fractional integrals, Katugampola fractional integrals

1. INTRODUCTION AND PRELIMINARIES

We will start with a definition of mathematical analysis that has a high degree precedence for the inequality theory.

A function $f : I \subseteq \mathbb{R} \rightarrow \mathbb{R}$ is said to be convex if the inequality

$$f(\lambda u + (1 - \lambda)v) \leq \lambda f(u) + (1 - \lambda)f(v)$$

holds for all $u, v \in I$ and $\lambda \in [0, 1]$.

This definition has been used in the celebrated Hermite-Hadamard inequality;

Let $f : I \subseteq \mathbb{R} \rightarrow \mathbb{R}$ be a convex function and $a, b \in I$ with $a < b$, then

$$f\left(\frac{a+b}{2}\right) \leq \frac{1}{b-a} \int_a^b f(x) dx \leq \frac{f(a) + f(b)}{2}. \quad (1.1)$$

In addition to giving upper and lower bounds for the mean value of a convex function, this double inequality has many applications.

Convexity plays an important role in different fields of pure and applied sciences. In recent years we have noticed that theory of convexity developed rapidly. Consequently several new generalizations of convex functions have been proposed in the literature. Recently İşcan [4] introduced the notion of harmonic convex function.

Definition 1. Let $I \subset \mathbb{R}/\{0\}$ be a real interval. A function $f : I \rightarrow \mathbb{R}$ is said to be harmonically convex, if

$$f\left(\frac{xy}{tx + (1-t)y}\right) \leq tf(y) + (1-t)f(x) \quad (1.2)$$

for all $x, y \in I$ and $t \in [0, 1]$.

The following theorem involve a different variant of Hadamard's inequality for harmonically convex functions.

Theorem 1 ([4]). Let $I \subset \mathbb{R}/\{0\} \rightarrow \mathbb{R}$ be a harmonically convex function and $a, b \in I$ with $a < b$. If $f \in L[a, b]$ then the following inequalities hold.

$$f\left(\frac{2ab}{a+b}\right) \leq \frac{ab}{b-a} \int_a^b \frac{f(x)}{x^2} dx \leq \frac{f(a) + f(b)}{2}.$$

To prove our results, we will use the following concepts and definitions. The Beta function [11, p.18]:

$$B(a, b) = \frac{\Gamma(a)\Gamma(b)}{\Gamma(a+b)} = \int_0^1 t^{a-1} (1-t)^{b-1} dt, \quad a, b > 0,$$

where $\Gamma(\alpha) = \int_0^\infty e^{-t} t^{\alpha-1} dt$ is Gamma function.

The hypergeometric function [7]:

$${}_2F_1(a, b; c; z) = \frac{1}{\beta(b, c-b)} \int_0^1 t^{b-1} (1-t)^{c-b-1} (1-zt)^{-a} dt, \quad c > b > 0, \quad z < 1.$$

Lemma 1 ([10]). For $0 < \alpha \leq 1$ and $0 \leq a < b$, we have

$$|a^\alpha - b^\alpha| \leq (b-a)^\alpha.$$

Definition 2. Let $f \in L_1[a, b]$. The Riemann-Liouville integrals $J_{a+}^\mu f$ and $J_{b-}^\mu f$ of order $\alpha > 0$ are defined by

$$J_{a+}^\mu f(x) = \frac{1}{\Gamma(\mu)} \int_a^x (x-t)^{\mu-1} f(t) dt, \quad x > a$$

and

$$J_{b-}^\mu f(x) = \frac{1}{\Gamma(\mu)} \int_x^b (t-x)^{\mu-1} f(t) dt, \quad x < b$$

respectively where $\Gamma(\mu) = \int_0^\infty e^{-t} t^{\mu-1} dt$. Here $J_{a+}^0 f(x) = J_{b-}^0 f(x) = f(x)$

In the case of $\mu = 1$, the fractional integral reduces to classical integral.

The great impact of fractional calculus in pure and applied sciences can not be denied. Resultantly many researchers used the techniques of fractional calculus intensively to get the new refinements of the previously known results. For example, we refer the reader to [1-3] and references cited therein. In [12], Sarikaya et. al. proved a new

version of Hermite-Hadamard's inequalities in Riemann-Liouville fractional integral form as follows:

Theorem 2. Let $f : [a, b] \rightarrow \mathbb{R}$ be a positive function with $0 \leq a < b$ and $f \in L_1[a, b]$. If f is a convex function on $[a, b]$, then the following inequalities for fractional integrals holds:

$$f\left(\frac{a+b}{2}\right) \leq \frac{\Gamma(\alpha+1)}{2(b-a)^\alpha} [J_{a+}^\alpha f(b) + J_{b-}^\alpha f(a)] \leq \frac{f(a) + f(b)}{2} \quad (1.3)$$

with $\alpha > 0$.

For further results related to Hermite-Hadamard type inequalities involving fractional integrals on can see [8, 9, 12–19].

In [5], Iscan et al. gave a generalization of (1.3) for harmonically convex functions as follows:

Theorem 3. Let $f : I \subset (0, \infty) \rightarrow \mathbb{R}$ be a function such that $f \in L[a, b]$, where $a, b \in I$ with $a < b$. If f is a harmonically convex function on $[a, b]$, then the following inequalities for fractional integrals hold:

$$\begin{aligned} f\left(\frac{2ab}{a+b}\right) &\leq \frac{\Gamma(\alpha+1)}{2} \left(\frac{ab}{b-a}\right)^\alpha \left\{ J_{1/a-}^\alpha (f \circ g)(1/b) + J_{1/b+}^\alpha (f \circ g)(1/a) \right\} \\ &\leq \frac{f(a) + f(b)}{2} \end{aligned} \quad (1.4)$$

where $g(x) = 1/x$.

Katugampola gave a new fractional integral that generalizes the Riemann-Liouville and the Hadamard fractional integrals into a single form.

Definition 3 ([6]). Let $[a, b] \subset \mathbb{R}$ be a finite interval. Then, the left- and right-side Katugampola fractional integrals of order $(\alpha > 0)$ of $f \in X_c^\rho(a, b)$ are defined:

$${}^\rho J_{a+}^\alpha f(x) = \frac{\rho^{1-\alpha}}{\Gamma(\alpha)} \int_a^x \frac{t^{\rho-1}}{(x^\rho - t^\rho)^{1-\alpha}} f(t) dt$$

and

$${}^\rho J_{b-}^\alpha f(x) = \frac{\rho^{1-\alpha}}{\Gamma(\alpha)} \int_x^b \frac{t^{\rho-1}}{(t^\rho - x^\rho)^{1-\alpha}} f(t) dt$$

with $a < x < b$ and $\rho > 0$, if the integral exist.

Theorem 4 ([6]). Let $\alpha > 0$ and $\rho > 0$. Then for $x > a$,

1. $\lim_{\rho \rightarrow 1} {}^\rho J_{a+}^\alpha f(x) = J_{a+}^\alpha f(x)$,
2. $\lim_{\rho \rightarrow 0+} {}^\rho J_{a+}^\alpha f(x) = H_{a+}^\alpha f(x)$.

Similar results also hold for right-sided operators.

The main purpose of this paper is to establish Hermite-Hadamard's inequalities for harmonically convex functions via Katugampola fractional integral. We also obtain Hermite-Hadamard type inequalities of these classes functions.

2. HERMITE-HADAMARD INEQUALITIES FOR HARMONICALLY CONVEXITY VIA KATUGAMPOLA FRACTIONAL INTEGRALS

Consider the space $X_c^p(a, b)$ ($c \in \mathbb{R}$, $1 \leq p \leq \infty$) consist of those complex-valued Lebesgue measurable functions φ on (a, b) for which $\|\varphi\|_{X_c^p} < \infty$, with

$$\|\varphi\|_{X_c^p} = \left(\int_a^b |x^c \varphi(x)|^p \frac{dx}{x} \right)^{1/p} \quad (1 \leq p < \infty)$$

and

$$\|\varphi\|_{X_c^p} = \text{esssup}_{x \in (a,b)} [x^c |\varphi(x)|].$$

Hermite-Hadamard's inequalities for harmonically convex functions can be represented in Katugampola fractional integral forms as follows:

Theorem 5. *Let $\alpha > 0$ and $\rho > 0$. Let $f : I \subset (0, \infty) \rightarrow \mathbb{R}$ be a function such that $f \in X_c^p(a^\rho, b^\rho)$, where $a^\rho, b^\rho \in I$ with $a < b$. If f is a harmonically convex function on $[a, b]$, then the following inequalities hold:*

$$\begin{aligned} & f\left(\frac{2a^\rho b^\rho}{a^\rho + b^\rho}\right) \\ & \leq \frac{\rho^\alpha \Gamma(\alpha + 1)}{2} \left(\frac{a^\rho b^\rho}{b^\rho - a^\rho}\right)^\alpha \left\{ {}^\rho J_{1/a^-}^\alpha (f \circ g)(1/b) + {}^\rho J_{1/b^+}^\alpha (f \circ g)(1/a) \right\} \quad (2.1) \\ & \leq \frac{f(a^\rho) + f(b^\rho)}{2}. \end{aligned}$$

where $g(x) = 1/x^\rho$.

Proof. Let $t \in [0, 1]$. Consider $x, y \in [a, b]$, $a \geq 0$, choosing $x^\rho = \frac{a^\rho b^\rho}{t^\rho b^\rho + (1-t^\rho)a^\rho}$, $y^\rho = \frac{a^\rho b^\rho}{t^\rho a^\rho + (1-t^\rho)b^\rho}$. Since f is harmonically convex function on $[a, b]$, and from definition, we can write

$$f\left(\frac{2x^\rho y^\rho}{x^\rho + y^\rho}\right) \leq \frac{f(x^\rho) + f(y^\rho)}{2}$$

Then we have

$$f\left(\frac{2a^\rho b^\rho}{a^\rho + b^\rho}\right) \leq \frac{f\left(\frac{a^\rho b^\rho}{t^\rho b^\rho + (1-t^\rho)a^\rho}\right) + f\left(\frac{a^\rho b^\rho}{t^\rho a^\rho + (1-t^\rho)b^\rho}\right)}{2} \quad (2.2)$$

Multiplying both sides of (2.2) by $t^{\rho\alpha-1}$, then integrating the resulting inequality with respect to t over $[0, 1]$, we obtain

$$f\left(\frac{2a^\rho b^\rho}{a^\rho + b^\rho}\right)$$

$$\begin{aligned}
&\leq \frac{\rho\alpha}{2} \left\{ \int_0^1 t^{\rho\alpha-1} f\left(\frac{a^\rho b^\rho}{t^\rho b^\rho + (1-t^\rho)a^\rho}\right) dt + \int_0^1 t^{\rho\alpha-1} f\left(\frac{a^\rho a^\rho}{t^\rho b^\rho + (1-t^\rho)b^\rho}\right) dt \right\} \\
&= \frac{\rho\alpha}{2} \left(\frac{a^\rho b^\rho}{b^\rho - a^\rho}\right)^\alpha \left\{ \int_{1/b}^{1/a} \frac{x^{\rho-1}}{(x^\rho - \frac{1}{b^\rho})^{1-\alpha}} f\left(\frac{1}{x^\rho}\right) dx \right. \\
&\quad \left. + \int_{1/a}^{1/b} \frac{x^{\rho-1}}{(\frac{1}{a^\rho} - x^\rho)^{1-\alpha}} f\left(\frac{1}{x^\rho}\right) dx \right\} \\
&= \frac{\rho^\alpha \Gamma(\alpha+1)}{2} \left(\frac{a^\rho b^\rho}{b^\rho - a^\rho}\right)^\alpha \left\{ {}^\rho J_{1/a-}^\alpha (f \circ g)(1/b) + {}^\rho J_{1/b+}^\alpha (f \circ g)(1/a) \right\}
\end{aligned}$$

where $g(x) = 1/x^\rho$. So the first inequality is proved.

For the proof of the second inequality in (2.1), we first note that that for a harmonically convex function f , we have

$$f\left(\frac{a^\rho b^\rho}{t^\rho b^\rho + (1-t^\rho)a^\rho}\right) \leq t^\rho f(a^\rho) + (1-t^\rho)b^\rho$$

and

$$f\left(\frac{a^\rho b^\rho}{t^\rho a^\rho + (1-t^\rho)b^\rho}\right) \leq t^\rho f(b^\rho) + (1-t^\rho)a^\rho.$$

By adding these inequalities, we have

$$f\left(\frac{a^\rho b^\rho}{t^\rho b^\rho + (1-t^\rho)a^\rho}\right) + f\left(\frac{a^\rho b^\rho}{t^\rho a^\rho + (1-t^\rho)b^\rho}\right) \leq f(a^\rho) + f(b^\rho). \quad (2.3)$$

Then multiplying both sides of (2.3) by $t^{\rho\alpha-1}$, and integrating the resulting inequality with respect to t over $[0, 1]$, we get

$$\begin{aligned}
&\int_0^1 f\left(\frac{a^\rho b^\rho}{t^\rho b^\rho + (1-t^\rho)a^\rho}\right) t^{\rho\alpha-1} dt + \int_0^1 f\left(\frac{a^\rho b^\rho}{t^\rho a^\rho + (1-t^\rho)b^\rho}\right) t^{\rho\alpha-1} dt \\
&\leq [f(a) + f(b)] \int_0^1 t^{\rho\alpha-1} dt
\end{aligned}$$

i.e.

$$\begin{aligned}
&\frac{\rho^\alpha \Gamma(\alpha+1)}{2} \left(\frac{a^\rho b^\rho}{b^\rho - a^\rho}\right)^\alpha \left\{ {}^\rho J_{1/a-}^\alpha (f \circ g)(1/b) + {}^\rho J_{1/b+}^\alpha (f \circ g)(1/a) \right\} \\
&\leq \frac{f(a) + f(b)}{2}.
\end{aligned}$$

The proof is completed. \square

Remark 1. In Theorem 5, taking limit $\rho \rightarrow 1$ we obtain inequality of (1.4).

3. HERMITE-HADAMARD TYPE INEQUALITIES FOR KATUGAMPOLA FRACTIONAL INTEGRALS

Let $f : I \subset (0, \infty) \rightarrow \mathbb{R}$ be a differentiable function on I° , the interior of I , throughout this section we will take

$$I_f(g; \alpha, a, b) = \frac{f(a^\rho) + b^\rho}{2} - \frac{\rho^\alpha \Gamma(\alpha + 1)}{2} \left(\frac{a^\rho b^\rho}{b^\rho - a^\rho} \right)^\alpha \left\{ {}^\rho J_{1/a^-}^\alpha (f \circ g)(1/b) + {}^\rho J_{1/b^+}^\alpha (f \circ g)(1/a) \right\},$$

where $a^\rho, b^\rho \in I$ with $a < b$. $g(x) = 1/x^\rho$ and Γ is Euler Gamma function.

Lemma 2. Let $\alpha > 0$ and $\rho > 0$. Let $f : I \subset (0, \infty) \rightarrow \mathbb{R}$ be a differentiable function such that $f \in X_c^\rho(a^\rho, b^\rho)$, where $a^\rho, b^\rho \in I$ with $a < b$. Then the following equality holds:

$$I_f(g; \alpha, a, b) = \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \int_0^1 \frac{[t^{\rho\alpha} - (1-t^\rho)^\alpha] t^{\rho-1}}{[t^\rho a^\rho + (1-t^\rho) b^\rho]^2} f' \left(\frac{a^\rho b^\rho}{t^\rho a^\rho + (1-t^\rho) b^\rho} \right) dt. \quad (3.1)$$

Proof. Let $A_t = t^\rho a^\rho + (1-t^\rho) b^\rho$ and $B_t = t^\rho b^\rho + (1-t^\rho) a^\rho$. It suffices to note that

$$\begin{aligned} I_f(g; \alpha, a, b) &= \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \int_0^1 \frac{[t^{\rho\alpha} - (1-t^\rho)^\alpha] t^{\rho-1}}{[t^\rho a^\rho + (1-t^\rho) b^\rho]^2} f' \left(\frac{a^\rho b^\rho}{t^\rho a^\rho + (1-t^\rho) b^\rho} \right) dt \\ &= \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \int_0^1 \frac{t^{\rho\alpha} t^{\rho-1}}{A_t^2} f' \left(\frac{a^\rho b^\rho}{A_t} \right) dt \\ &\quad - \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \int_0^1 \frac{(1-t^\rho)^\alpha t^{\rho-1}}{A_t^2} f' \left(\frac{a^\rho b^\rho}{A_t} \right) dt \\ &= I_1 + I_2. \end{aligned} \quad (3.2)$$

By integrating by part, we get

$$\begin{aligned} I_1 &= \frac{1}{2} \left[t^{\rho\alpha} f \left(\frac{a^\rho b^\rho}{A_t} \right) \Big|_0^1 - \rho\alpha \int_0^1 t^{\rho\alpha-1} f \left(\frac{a^\rho b^\rho}{A_t} \right) dt \right] \\ &= \frac{1}{2} \left[f(b^\rho) - \rho\alpha \left(\frac{a^\rho b^\rho}{b^\rho - a^\rho} \right)^\alpha \int_{1/b}^{1/a} \frac{x^{\rho-1}}{(x^\rho - \frac{1}{b^\rho})^{1-\alpha}} f \left(\frac{1}{x^\rho} \right) dx \right] \\ &= \frac{1}{2} \left[f(b^\rho) - \rho^\alpha \Gamma(\alpha + 1) \left(\frac{a^\rho b^\rho}{b^\rho - a^\rho} \right)^\alpha {}^\rho J_{1/a^-}^\alpha (f \circ g)(1/b) \right] \end{aligned} \quad (3.3)$$

and similarly we get

$$\begin{aligned}
 I_2 &= -\frac{1}{2} \left[(1-t^\rho)^\alpha f\left(\frac{a^\rho b^\rho}{A_t}\right) \Big|_0^1 + \rho\alpha \int_0^1 (1-t^\rho)^{\alpha-1} t^{\rho-1} f\left(\frac{a^\rho b^\rho}{A_t}\right) dt \right] \\
 &= \frac{1}{2} \left[f(a^\rho) - \rho\alpha \int_0^1 u^{\rho\alpha-1} f\left(\frac{a^\rho b^\rho}{B_t}\right) du \right] \\
 &= \frac{1}{2} \left[f(a^\rho) - \rho\alpha \left(\frac{a^\rho b^\rho}{b^\rho - a^\rho}\right)^\alpha \int_{1/a}^{1/b} \frac{x^{\rho-1}}{\left(\frac{1}{a^\rho} - x^\rho\right)^{1-\alpha}} f\left(\frac{1}{x^\rho}\right) dx \right] \\
 &= \frac{1}{2} \left[f(a^\rho) - \rho^\alpha \Gamma(\alpha + 1) \left(\frac{a^\rho b^\rho}{b^\rho - a^\rho}\right)^\alpha \mathcal{J}_{1/b+}^\alpha (f \circ g)(1/a) \right] \tag{3.4}
 \end{aligned}$$

Using (3.3) and (3.4) in (3.2), we get equality (3.1). □

Remark 2. In Lemma 2, taking limit $\rho \rightarrow 1$ we obtain inequality Lemma 3 in [5].

Theorem 6. Let $\alpha > 0$ and $\rho > 0$. Let $f : I \subset (0, \infty) \rightarrow \mathbb{R}$ be a differentiable function such that $f \in X_C^\rho(a^\rho, b^\rho)$, where $a^\rho, b^\rho \in I$ with $a < b$. If $|f|^q$ is a harmonically convex function on $[a, b]$ for some fixed $q \geq 1$, then the following inequalities holds:

$$\begin{aligned}
 |I_f(g; \alpha, a, b)| &\leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \Lambda_1^{1-1/q}(\alpha; a, b) \\
 &\quad \left(\Lambda_2(\alpha; a, b) |f'(b)|^q + \Lambda_3(\alpha; a, b) |f'(a)|^q \right)^{1/q} \tag{3.5}
 \end{aligned}$$

where

$$\begin{aligned}
 \Lambda_1(\alpha; a, b) &= \frac{b^{-2\rho}}{\rho(\alpha + 1)} \left[{}_2F_1\left(2, \alpha + 1; \alpha + 2; 1 - \frac{a^\rho}{b^\rho}\right) \right. \\
 &\quad \left. + {}_2F_1\left(2, 1; \alpha + 2; 1 - \frac{a^\rho}{b^\rho}\right) \right], \\
 \Lambda_2(\alpha; a, b) &= \frac{b^{-2\rho}}{\rho(\alpha + 2)} \left[{}_2F_1\left(2, \alpha + 2; \alpha + 3; 1 - \frac{a^\rho}{b^\rho}\right) \right. \\
 &\quad \left. + \frac{1}{\alpha + 1} {}_2F_1\left(2, 2; \alpha + 3; 1 - \frac{a^\rho}{b^\rho}\right) \right], \\
 \Lambda_3(\alpha; a, b) &= \frac{b^{-2\rho}}{\rho(\alpha + 2)} \left[\frac{1}{\alpha + 1} {}_2F_1\left(2, \alpha + 1; \alpha + 3; 1 - \frac{a^\rho}{b^\rho}\right) \right. \\
 &\quad \left. + {}_2F_1\left(2, 1; \alpha + 3; 1 - \frac{a^\rho}{b^\rho}\right) \right].
 \end{aligned}$$

Proof. Let $A_t = t^\rho a^\rho + (1 - t^\rho) b^\rho$. From Lemma 2, using the property of the modulus, the power mean inequality and the harmonically convexity of $|f|^q$, we get

$$|I_f(g; \alpha, a, b)|$$

$$\begin{aligned}
&\leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \int_0^1 \frac{|t^{\rho\alpha} - (1-t^\rho)^\alpha| |t^{\rho-1}|}{A_t^2} \left| f' \left(\frac{a^\rho b^\rho}{A_t} \right) \right| dt \\
&\leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \left(\int_0^1 \frac{|t^{\rho\alpha} - (1-t^\rho)^\alpha| |t^{\rho-1}|}{A_t^2} dt \right)^{1-1/q} \\
&\quad \times \left(\int_0^1 \frac{|t^{\rho\alpha} - (1-t^\rho)^\alpha| |t^{\rho-1}|}{A_t^2} \left| f' \left(\frac{a^\rho b^\rho}{A_t} \right) \right| dt \right)^{1/q} \\
&\leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \left(\int_0^1 \frac{|t^{\rho\alpha} + (1-t^\rho)^\alpha| |t^{\rho-1}|}{A_t^2} dt \right)^{1-1/q} \\
&\quad \times \left(\int_0^1 \frac{|t^{\rho\alpha} + (1-t^\rho)^\alpha| |t^{\rho-1}|}{A_t^2} \left(t^\rho |f'(b^\rho)|^q + (1-t^\rho) |f'(a^\rho)|^q \right) dt \right)^{1/q} \\
&\leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \Lambda_1^{1-1/q}(\alpha; a, b) \left(\Lambda_2(\alpha; a, b) |f'(b)|^q + \Lambda_3(\alpha; a, b) |f'(a)|^q \right)^{1/q}.
\end{aligned} \tag{3.6}$$

Calculating $\Lambda_1(\alpha; a, b)$, $\Lambda_2(\alpha; a, b)$ and $\Lambda_3(\alpha; a, b)$, we have

$$\begin{aligned}
&\Lambda_1(\alpha; a, b) \\
&= \int_0^1 \frac{[t^{\rho\alpha} + (1-t^\rho)^\alpha] t^{\rho-1}}{A_t^2} dt \\
&= b^{-2\rho} \int_0^1 (u^\alpha + (1-u)^\alpha) \left(1 - \left(1 - \frac{a^\rho}{b^\rho} \right) u \right)^{-2} dt \\
&= \frac{b^{-2\rho}}{\rho(\alpha+1)} \left[{}_2F_1 \left(2, \alpha+1; \alpha+2; 1 - \frac{a^\rho}{b^\rho} \right) + {}_2F_1 \left(2, 1; \alpha+2; 1 - \frac{a^\rho}{b^\rho} \right) \right].
\end{aligned} \tag{3.7}$$

Similarly, we get

$$\begin{aligned}
&\Lambda_2(\alpha; a, b) \\
&= \int_0^1 \frac{[t^{\rho\alpha} + (1-t^\rho)^\alpha] t^{\rho-1}}{A_t^2} t^\rho dt \\
&= \frac{b^{-2\rho}}{\rho(\alpha+2)} \left[{}_2F_1 \left(2, \alpha+2; \alpha+3; 1 - \frac{a^\rho}{b^\rho} \right) + \frac{1}{\alpha+1} {}_2F_1 \left(2, 2; \alpha+3; 1 - \frac{a^\rho}{b^\rho} \right) \right]
\end{aligned} \tag{3.8}$$

and

$$\begin{aligned}
&\Lambda_3(\alpha; a, b) \\
&= \int_0^1 \frac{[t^{\rho\alpha} + (1-t^\rho)^\alpha] t^{\rho-1}}{A_t^2} t^\rho dt
\end{aligned} \tag{3.9}$$

$$= \frac{b^{-2\rho}}{\rho(\alpha + 2)} \left[\frac{1}{\alpha + 1} {}_2F_1 \left(2, \alpha + 1; \alpha + 3; 1 - \frac{a^\rho}{b^\rho} \right) + {}_2F_1 \left(2, 1; \alpha + 3; 1 - \frac{a^\rho}{b^\rho} \right) \right]$$

So, if we use (3.7)-(3.9) in (3.6), we obtain the inequality of (3.5). This completes the proof. □

Remark 3. In Theorem 6, taking limit $\rho \rightarrow 1$ we obtain Theorem 5 in [5].

Theorem 7. Let $\alpha > 0$ and $\rho > 0$. Let $f : I \subset (0, \infty) \rightarrow \mathbb{R}$ be a differentiable function such that $f \in X_c^\rho(a^\rho, b^\rho)$, where $a^\rho, b^\rho \in I$ with $a < b$. If $|f|^l$ is a harmonically convex function on $[a, b]$ for some fixed $l \geq 1$, then the following inequalities holds:

$$|I_f(g; \alpha, a, b)| \leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \Lambda_4^{1-1/q}(\alpha; a, b) \left(\Lambda_5(\alpha; a, b) |f'(b)|^q + \Lambda_6(\alpha; a, b) |f'(a)|^q \right)^{1/q} \tag{3.10}$$

where

$$\Lambda_4 = \frac{b^{-2\rho}}{\rho(\alpha + 1)} \left[{}_2F_1 \left(2, \alpha + 1; \alpha + 2; 1 - \frac{a^\rho}{b^\rho} \right) - {}_2F_1 \left(2, 1; \alpha + 2; 1 - \frac{a^\rho}{b^\rho} \right) + {}_2F_1 \left(2, 1; \alpha + 2; \frac{1}{2} \left(1 - \frac{a^\rho}{b^\rho} \right) \right) \right]$$

$$\Lambda_5 = \frac{b^{-2\rho}}{\rho(\alpha + 2)} \left[{}_2F_1 \left(2, \alpha + 2; \alpha + 3; 1 - \frac{a^\rho}{b^\rho} \right) - \frac{1}{\alpha + 1} {}_2F_1 \left(2, 2; \alpha + 3; 1 - \frac{a^\rho}{b^\rho} \right) + \frac{1}{2(\alpha + 1)} {}_2F_1 \left(2, 2; \alpha + 3; \frac{1}{2} \left(1 - \frac{a^\rho}{b^\rho} \right) \right) \right]$$

$$\Lambda_6 = \frac{b^{-2\rho}}{\rho(\alpha + 2)} \left[\frac{1}{\alpha + 1} {}_2F_1 \left(2, \alpha + 1; \alpha + 3; 1 - \frac{a^\rho}{b^\rho} \right) - {}_2F_1 \left(2, 1; \alpha + 3; 1 - \frac{a^\rho}{b^\rho} \right) + {}_2F_1 \left(2, 1; \alpha + 3; \frac{1}{2} \left(1 - \frac{a^\rho}{b^\rho} \right) \right) \right].$$

Proof. Let $A_t = t^\rho a^\rho + (1 - t^\rho) b^\rho$. From Lemma 2, using the property of the modulus, the power mean inequality and the harmonically convexity of $|f|^q$, we have

$$\begin{aligned} & |I_f(g; \alpha, a, b)| \\ & \leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \int_0^1 \frac{|t^{\rho\alpha} - (1 - t^\rho)^\alpha| |t^{\rho-1}|}{A_t^2} \left| f' \left(\frac{a^\rho b^\rho}{A_t} \right) \right| dt \\ & \leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \left(\int_0^1 \frac{|t^{\rho\alpha} - (1 - t^\rho)^\alpha| |t^{\rho-1}|}{A_t^2} dt \right)^{1-1/q} \end{aligned}$$

$$\begin{aligned}
& \times \left(\int_0^1 \frac{|t^{\rho\alpha} - (1-t^\rho)^\alpha| |t^{\rho-1}|}{A_t^2} \left| f' \left(\frac{a^\rho b^\rho}{A_t} \right) \right| dt \right)^{1/q} \\
& \leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \left(\int_0^1 \frac{|t^{\rho\alpha} - (1-t^\rho)^\alpha| |t^{\rho-1}|}{A_t^2} dt \right)^{1-1/q} \\
& \quad \times \left(\int_0^1 \frac{|t^{\rho\alpha} - (1-t^\rho)^\alpha| |t^{\rho-1}|}{A_t^2} \left(t^\rho |f'(b^\rho)|^q + (1-t^\rho) |f'(a^\rho)|^q \right) dt \right)^{1/q} \\
& \leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} K_1^{1-1/q}(\alpha; a, b) \left(K_2(\alpha; a, b) |f'(b)|^q + K_3(\alpha; a, b) |f'(a)|^q \right)^{1/q}.
\end{aligned} \tag{3.11}$$

Calculating K_1 , K_2 and K_3 , by Lemma 1, we get

$$\begin{aligned}
K_1 &= \int_0^1 \frac{|t^{\rho\alpha} - (1-t^\rho)^\alpha| |t^{\rho-1}|}{A_t^2} dt \\
&= \int_0^{1/2} \frac{((1-t^\rho)^\alpha - t^{\rho\alpha}) t^{\rho-1}}{A_t^2} dt + \int_{1/2}^1 \frac{(t^{\rho\alpha} - (1-t^\rho)^\alpha) t^{\rho-1}}{A_t^2} dt \\
&= \int_0^1 \frac{(t^{\rho\alpha} - (1-t^\rho)^\alpha) t^{\rho-1}}{A_t^2} dt + 2 \int_0^{1/2} \frac{((1-t^\rho)^\alpha - t^{\rho\alpha}) t^{\rho-1}}{A_t^2} dt \\
&\leq \int_0^1 u^\alpha A_u^{-2} du - \int_0^1 (1-u)^\alpha A_u^{-2} du + 2 \int_0^{1/2} (1-2u)^\alpha A_u^{-2} du \\
&= \frac{b^{-2\rho}}{\rho(\alpha+1)} \left[{}_2F_1 \left(2, \alpha+1; \alpha+2; 1 - \frac{a^\rho}{b^\rho} \right) - {}_2F_1 \left(2, 1; \alpha+2; 1 - \frac{a^\rho}{b^\rho} \right) \right. \\
&\quad \left. + {}_2F_1 \left(2, 1; \alpha+2; \frac{1}{2} \left(1 - \frac{a^\rho}{b^\rho} \right) \right) \right].
\end{aligned} \tag{3.12}$$

and similarly we obtain

$$\begin{aligned}
K_2 &= \int_0^1 \frac{|t^{\rho\alpha} - (1-t^\rho)^\alpha| |t^{\rho-1}|}{A_t^2} t^\rho dt \\
&\leq \int_0^1 u^{\alpha+1} A_u^{-2} du - \int_0^1 (1-u)^\alpha u A_u^{-2} du + 2 \int_0^{1/2} (1-2u)^\alpha u A_u^{-2} du \\
&= \frac{b^{-2\rho}}{\rho(\alpha+2)} \left[{}_2F_1 \left(2, \alpha+2; \alpha+3; 1 - \frac{a^\rho}{b^\rho} \right) - \frac{1}{\alpha+1} {}_2F_1 \left(2, 2; \alpha+3; 1 - \frac{a^\rho}{b^\rho} \right) \right. \\
&\quad \left. + \frac{1}{2(\alpha+1)} {}_2F_1 \left(2, 2; \alpha+3; \frac{1}{2} \left(1 - \frac{a^\rho}{b^\rho} \right) \right) \right],
\end{aligned} \tag{3.13}$$

and

$$\begin{aligned}
 K_3 &= \int_0^1 \frac{|t^{\rho\alpha} - (1-t^\rho)^\alpha| |t^{\rho-1}|}{A_t^2} (1-t)^\rho dt \\
 &\leq \int_0^1 t^\alpha (1-u) A_u^{-2} du - \int_0^1 (1-u)^{\alpha+1} A_u^{-2} du + 2 \int_0^{1/2} (1-2u)^\alpha (1-u) A_u^{-2} du \\
 &= \frac{b^{-2\rho}}{\rho(\alpha+2)} \left[\frac{1}{\alpha+1} {}_2F_1 \left(2, \alpha+1; \alpha+3; 1 - \frac{a^\rho}{b^\rho} \right) - {}_2F_1 \left(2, 1; \alpha+3; 1 - \frac{a^\rho}{b^\rho} \right) \right. \\
 &\quad \left. + {}_2F_1 \left(2, 1; \alpha+3; \frac{1}{2} \left(1 - \frac{a^\rho}{b^\rho} \right) \right) \right]. \tag{3.14}
 \end{aligned}$$

So, if we use (3.12)-(3.14) in (3.11), we get the inequality (3.10). □

Remark 4. In Theorem 7, taking limit $\rho \rightarrow 1$ we obtain Theorem 6 in [5].

Theorem 8. Let $\alpha > 0$ and $\rho > 0$. Let $f : I \subset (0, \infty) \rightarrow \mathbb{R}$ be a differentiable function such that $f \in X_c^\rho(a^\rho, b^\rho)$, where $a^\rho, b^\rho \in I$ with $a < b$. If $|f|^l$ is a harmonically convex function on $[a, b]$ for some fixed $l > 1, 1/k + 1/l = 1$, then the following inequalities holds:

$$|I_f(g; \alpha, a, b)| = \frac{a^\rho(b^\rho - a^\rho)}{2b^\rho} \left(\Lambda_7^{1/k} + \Lambda_8^{1/k} \right) \left(\frac{|f'(a^\rho)|^l + |f'(b^\rho)|^l}{\rho+1} \right)^{1/l} \tag{3.15}$$

where

$$\begin{aligned}
 \Lambda_7 &= B \left(\frac{\rho k - k + 1}{\rho}, \alpha k + 1 \right) {}_2F_1 \left(2k, \frac{\rho k - k + 1}{\rho}; \alpha k + k + 1 + \frac{1-k}{\rho}; 1 - \frac{a^\rho}{b^\rho} \right) \\
 \Lambda_8 &= \frac{1}{\left(\alpha k + k + \frac{1-k}{\rho} \right)} {}_2F_1 \left(2k, \alpha k + k + \frac{1-k}{\rho}; \alpha k + k + 1 + \frac{1-k}{\rho}; 1 - \frac{a^\rho}{b^\rho} \right)
 \end{aligned}$$

Proof. Let $A_t = t^\rho a^\rho + (1-t^\rho)b^\rho$. From Lemma 2, Hölder inequality and the harmonically convexity of $|f|^q$, we have

$$\begin{aligned}
 &|I_f(g; \alpha, a, b)| \\
 &\leq \frac{a^\rho b^\rho (b^\rho - a^\rho)}{2} \left[\int_0^1 \frac{t^{\rho\alpha} t^{\rho-1}}{A_t^2} \left| f' \left(\frac{a^\rho b^\rho}{A_t} \right) \right| dt + \int_0^1 \frac{(1-t^\rho)^\alpha t^{\rho-1}}{A_t^2} \left| f' \left(\frac{a^\rho b^\rho}{A_t} \right) \right| dt \right] \\
 &\leq \frac{a^\rho b^\rho (b^\rho - a^\rho)}{2} \left\{ \left(\int_0^1 \frac{t^{\rho\alpha} t^{k(\rho-1)}}{A_t^{2k}} dt \right)^{1/k} \left(\int_0^1 \left| f' \left(\frac{a^\rho b^\rho}{A_t^{2k}} \right) \right|^l dt \right)^{1/l} \right. \\
 &\quad \left. + \left(\int_0^1 \frac{(1-t^\rho)^\alpha t^{k(\rho-1)}}{A_t^{2k}} dt \right)^{1/k} \left(\int_0^1 \left| f' \left(\frac{a^\rho b^\rho}{A_t^{2k}} \right) \right|^l dt \right)^{1/l} \right\}
 \end{aligned}$$

$$\begin{aligned} &\leq \frac{a^\rho b^\rho (b^\rho - a^\rho)}{2} \left(K_4^{1/k} + K_5^{1/k} \right) \left(\int_0^1 \left[t^\rho |f'(b^\rho)|^l + (1-t^\rho) |f'(a^\rho)|^l \right] dt \right)^{1/l} \\ &\leq \frac{a^\rho b^\rho (b^\rho - a^\rho)}{2} \left(K_4^{1/k} + K_5^{1/k} \right) \left(\frac{|f'(a^\rho)|^l + |f'(b^\rho)|^l}{\rho + 1} \right)^{1/l}. \end{aligned} \quad (3.16)$$

Calculating K_4 and K_5 , we obtain

$$\begin{aligned} K_4 &= \int_0^1 \frac{(1-t^\rho)^{\alpha k} t^{k(\rho-1)}}{A_t^{2k}} dt \\ &= \frac{b^{-2\rho k}}{B\left(\frac{\rho k - k + 1}{\rho}, \alpha k + 1\right)} {}_2F_1\left(2k, \frac{\rho k - k + 1}{\rho}; \alpha k + k + 1 + \frac{1-k}{\rho}; 1 - \frac{a^\rho}{b^\rho}\right) \end{aligned} \quad (3.17)$$

$$\begin{aligned} K_5 &= \int_0^1 \frac{t^{\rho \alpha k} t^{k(\rho-1)}}{A_t^{2k}} dt \\ &= \left(\alpha k + k + \frac{1-k}{\rho} \right) b^{-2\rho k} {}_2F_1\left(2k, \alpha k + k + \frac{1-k}{\rho}; \alpha k + k + 1 + \frac{1-k}{\rho}; 1 - \frac{a^\rho}{b^\rho}\right) \end{aligned} \quad (3.18)$$

So, if we use (3.17) and (3.18) in (3.16), we get the inequality of (3.15). This completes the proof. \square

Remark 5. In Theorem 8, taking limit $\rho \rightarrow 1$ we obtain Theorem 7 in [5].

Theorem 9. Let $\alpha > 0$ and $\rho > 0$. Let $f : I \subset (0, \infty) \rightarrow \mathbb{R}$ be a differentiable function such that $f \in X_c^\rho(a^\rho, b^\rho)$, where $a^\rho, b^\rho \in I$ with $a < b$. If $|f|^l$ is a harmonically convex function on $[a, b]$ for some fixed $l > 1$, $1/k + 1/l = 1$, then the following inequalities holds:

$$|I_f(g; \alpha, a, b)| \leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \Lambda_9^{1/k} \left(\Lambda_{10} |f'(b^\rho)|^l + \Lambda_{11} |f'(a^\rho)|^l \right)^{1/l} \quad (3.19)$$

where

$$\Lambda_9 = b^{-2\rho k} {}_2F_1\left(2k, \frac{1}{\rho}; \frac{\rho+1}{\rho}; 1 - \frac{a^\rho}{b^\rho}\right) \quad (3.20)$$

$$\Lambda_{10} = \frac{1}{\rho 2^{\frac{\rho+1}{\rho}}} B\left(\frac{\rho+1}{\rho}, \alpha l + 1\right) + \frac{\alpha l + 1}{2\rho} {}_2F_1\left(\frac{-1}{\rho}, 1; \alpha l + 2; \frac{1}{2}\right) \quad (3.21)$$

$$\begin{aligned} \Lambda_{11} &= \frac{1}{\rho 2^{\frac{1}{\rho}}} B\left(\frac{1}{\rho}, \alpha l + 1\right) {}_2F_1\left(-1, \frac{1}{\rho}; \alpha l + \frac{1}{\rho} + 1; \frac{1}{2}\right) \\ &\quad + \frac{(\alpha l + 1)(\alpha l + 2)}{\rho 2^{\frac{2-\rho}{\rho}}} {}_2F_1\left(\frac{1-\rho}{\rho}, 2; \alpha l + 3; \frac{1}{2}\right). \end{aligned} \quad (3.22)$$

Proof. Let $A_t = t^\rho a^\rho + (1-t^\rho)b^\rho$. From Lemma 1, Lemma 2, Hölder inequality and the harmonically convexity of $|f|^q$, we have

$$\begin{aligned}
|I_f(g; \alpha, a, b)| &\leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \int_0^1 \frac{|t^{\rho\alpha} - (1-t^\rho)^\alpha| |t^{\rho-1}|}{A_t^2} \left| f' \left(\frac{a^\rho b^\rho}{A_t} \right) \right| dt \\
&\leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \left(\int_0^1 \frac{1}{A_t^{2k}} dt \right)^{1/k} \\
&\quad \times \left(\int_0^1 |t^{\rho\alpha} - (1-t^\rho)^\alpha|^l |t^{\rho-1}|^l \left| f' \left(\frac{a^\rho b^\rho}{A_t} \right) \right|^l dt \right)^{1/l} \\
&\leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \left(\int_0^1 \frac{1}{A_t^{2k}} dt \right)^{1/k} \\
&\quad \times \left(\int_0^1 |1-2t^\rho|^{\alpha l} \left[t^\rho |f'(b^\rho)|^l + (1-t^\rho) |f'(a^\rho)|^l \right] dt \right)^{1/l} \\
&\leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} K_6^{1/k} \left(K_7 |f'(b^\rho)|^l + K_8 |f'(a^\rho)|^l \right)^{1/l}. \quad (3.23)
\end{aligned}$$

where

$$\Lambda_9 = \int_0^1 \frac{1}{A_t^{2k}} dt = b^{-2\rho k} {}_2F_1 \left(2k, \frac{1}{\rho}; \frac{\rho+1}{\rho}; 1 - \frac{a^\rho}{b^\rho} \right) \quad (3.24)$$

$$\begin{aligned}
\Lambda_{10} &= \int_0^1 |1-2t^\rho|^{\alpha l} t^\rho dt \\
&= \int_0^{1/2^{1/\rho}} (1-2t^\rho)^{\alpha l} t^\rho dt + \int_{1/2^{1/\rho}}^1 (2t^\rho-1)^{\alpha l} t^\rho dt \\
&= \frac{1}{\rho 2^{\frac{\rho+1}{\rho}}} B \left(\frac{\rho+1}{\rho}, \alpha l + 1 \right) + \frac{\alpha l + 1}{2\rho} {}_2F_1 \left(\frac{-1}{\rho}, 1; \alpha l + 2; \frac{1}{2} \right) \quad (3.25)
\end{aligned}$$

$$\begin{aligned}
\Lambda_{11} &= \int_0^1 |1-2t^\rho|^{\alpha l} (1-t^\rho) dt \\
&= \int_0^{1/2^{1/\rho}} (1-2t^\rho)^{\alpha l} (1-t^\rho) dt + \int_{1/2^{1/\rho}}^1 (2t^\rho-1)^{\alpha l} (1-t^\rho) dt \\
&= \frac{1}{\rho 2^{\frac{1}{\rho}}} B \left(\frac{1}{\rho}, \alpha l + 1 \right) {}_2F_1 \left(-1, \frac{1}{\rho}; \alpha l + \frac{1}{\rho} + 1; \frac{1}{2} \right) \\
&\quad + \frac{(\alpha l + 1)(\alpha l + 2)}{\rho 2^{\frac{2-\rho}{\rho}}} {}_2F_1 \left(\frac{1-\rho}{\rho}, 2; \alpha l + 3; \frac{1}{2} \right). \quad (3.26)
\end{aligned}$$

So, if we use (3.24)-(3.26) in (3.23), we get desired result. \square

Remark 6. In Theorem 9, taking limit $\rho \rightarrow 1$ we obtain Theorem 8 in [5].

Theorem 10. Let $\alpha > 0$ and $\rho > 0$. Let $f : I \subset (0, \infty) \rightarrow \mathbb{R}$ be a differentiable function such that $f \in X_c^\rho(a^\rho, b^\rho)$, where $a^\rho, b^\rho \in I$ with $a < b$. If $|f|^q$ is a harmonically convex function on $[a, b]$ for some fixed $q > 1$, $1/k + 1/l = 1$, then the following inequalities holds:

$$|I_f(g; \alpha, a, b)| = \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \Lambda_{12}^{1/k} \left(\Lambda_{13} |f'(b^\rho)|^l + \Lambda_{14} |f'(a^\rho)|^l \right)^{1/l} \quad (3.27)$$

where

$$\begin{aligned} \Lambda_{12} &= \frac{1}{\rho 2^{(k\rho-k+1)/\rho}} B\left(\frac{k\rho-k+1}{\rho}, \alpha k + 1\right) \\ &\quad + \frac{1}{\rho 2^\rho} {}_2F_1\left(\frac{k+\rho-k\rho-1}{\rho}, 1; \alpha k + 2; \frac{1}{2}\right) \\ \Lambda_{13} &= \frac{1}{(\rho+1)b^{2\rho l}} {}_2F_1\left(2l, \frac{\rho+1}{\rho}; \frac{2\rho+1}{\rho}; 1 - \frac{a^\rho}{b^\rho}\right) \\ \Lambda_{14} &= \frac{\rho}{(\rho+1)b^{2\rho l}} {}_2F_1\left(2l, \frac{1}{\rho}; \frac{2\rho+1}{\rho}; 1 - \frac{a^\rho}{b^\rho}\right). \end{aligned}$$

Proof. Let $A_t = t^\rho a^\rho + (1-t^\rho)b^\rho$. From Lemma 1, Lemma 2, Hölder inequality and the harmonically convexity of $|f|^q$, we have

$$\begin{aligned} |I_f(g; \alpha, a, b)| &\leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \int_0^1 \frac{|t^{\rho\alpha} - (1-t^\rho)^\alpha| |t^{\rho-1}|}{A_t^2} \left| f' \left(\frac{a^\rho b^\rho}{A_t} \right) \right| dt \\ &\leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \left(\int_0^1 |t^{\rho\alpha} - (1-t^\rho)^\alpha|^k |t^{\rho-1}|^k dt \right)^{1/k} \\ &\quad \times \left(\int_0^1 \frac{1}{A_t^{2l}} \left| f' \left(\frac{a^\rho b^\rho}{A_t} \right) \right|^l dt \right)^{1/l} \\ &\leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} \left(\int_0^1 |(2t^\rho - 1)|^{\alpha k} t^{k(\rho-1)} dt \right)^{1/k} \\ &\quad \times \left(\int_0^1 \frac{1}{A_t^{2l}} \left[t^\rho |f'(b^\rho)|^l + (1-t^\rho) |f'(a^\rho)|^l \right] dt \right)^{1/l} \\ &\leq \frac{\rho a^\rho b^\rho (b^\rho - a^\rho)}{2} K_6^{1/k} \left(K_7 |f'(b^\rho)|^l + K_8 |f'(a^\rho)|^l \right)^{1/l}. \quad (3.28) \end{aligned}$$

where

$$\Lambda_{12} = \int_0^1 |(2t^\rho - 1)|^{\alpha k} t^{k(\rho-1)} dt$$

$$\begin{aligned}
&= \int_0^{1/2^{1/\rho}} (1-2t^\rho)^{\alpha k} t^{k(\rho-1)} dt + \int_{1/2^{1/\rho}}^1 (2t^\rho-1)^{\alpha k} t^{k(\rho-1)} dt \\
&= \frac{1}{\rho 2^{(k\rho-k+1)/\rho}} B\left(\frac{k\rho-k+1}{\rho}, \alpha k+1\right) \tag{3.29}
\end{aligned}$$

$$+ \frac{1}{\rho 2^\rho} {}_2F_1\left(\frac{k+\rho-k\rho-1}{\rho}, 1; \alpha k+2; \frac{1}{2}\right), \tag{3.30}$$

$$\begin{aligned}
\Lambda_{13} &= \int_0^1 t^\rho A_t^{-2l} dt \\
&= \frac{1}{(\rho+1)b^{2\rho l}} {}_2F_1\left(2l, \frac{\rho+1}{\rho}; \frac{2\rho+1}{\rho}; 1-\frac{a^\rho}{b^\rho}\right) \tag{3.31}
\end{aligned}$$

$$\begin{aligned}
\Lambda_{14} &= \int_0^1 (1-t^\rho) A_t^{-2l} dt \\
&= \frac{\rho}{(\rho+1)b^{2\rho l}} {}_2F_1\left(2l, \frac{1}{\rho}; \frac{2\rho+1}{\rho}; 1-\frac{a^\rho}{b^\rho}\right) \tag{3.32}
\end{aligned}$$

So, if we use (3.30)-(3.32) in (3.28), we obtain desired result. \square

Remark 7. In Theorem 10, taking limit $\rho \rightarrow 1$ we obtain Theorem 9 in [5].

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