

Lower Bounds on Signed Total Double Roman k -domination in Graphs

Laila Shahbazi^a, Hossein Abdollahzadeh Ahangar^{b*}, Rana Khoeilar^a,
Seyed Mahmoud Sheikholeslami^a

^aDepartment of Mathematics, Azarbaijan Shahid Madani University, Tabriz,
I.R. Iran

^bDepartment of Mathematics, Babol Noshirvani University of Technology,
Shariati Ave., Babol, I.R. Iran, Postal Code: 47148-71167

E-mail: l.shahbazi@azaruniv.ac.ir

E-mail: ha.ahangar@nit.ac.ir

E-mail: khoeilar@azaruniv.ac.ir

E-mail: s.m.sheikholeslami@azaruniv.ac.ir

ABSTRACT. A signed total double Roman k -dominating function (STDRkDF) on an isolated-free graph $G = (V, E)$ is a function $f : V(G) \rightarrow \{-1, 1, 2, 3\}$ such that (i) every vertex v with $f(v) = -1$ has at least two neighbors assigned 2 under f or at least one neighbor w with $f(w) = 3$, (ii) every vertex v with $f(v) = 1$ has at least one neighbor w with $f(w) \geq 2$ and (iii) $\sum_{u \in N(v)} f(u) \geq k$ holds for any vertex v . The weight of an STDRkDF is the value $f(V(G)) = \sum_{u \in V(G)} f(u)$. The signed total double Roman k -domination number $\gamma_{stdR}^k(G)$ is the minimum weight among all signed total double Roman k -dominating functions on G . In this paper we present sharp lower bounds for $\gamma_{stdR}^2(G)$ and $\gamma_{stdR}^3(G)$ in terms of the order and the size of the graph G .

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*Corresponding Author

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1. INTRODUCTION

In this paper we only consider finite isolated free graphs without loops and multiple edges. For notation and graph theory terminology we follow [15] in general. Let $G = (V, E)$ be a simple graphs without isolated vertices with vertex set $V = V(G)$ and edge set $E = E(G)$. The order $|V|$ of G is denoted by $n = n(G)$. For every vertex $v \in V$, the *open neighborhood* $N(v)$ is the set $\{u \in V(G) \mid uv \in E(G)\}$ and the *closed neighborhood* of v is the set $N[v] = N(v) \cup \{v\}$. The *degree* of a vertex $v \in V$ is $\deg_G(v) = |N(v)|$. The *minimum degree* and the *maximum degree* of a graph G are denoted by $\delta = \delta(G)$ and $\Delta = \Delta(G)$, respectively. For any set S of vertices of a graph G and any vertex $v \in V(G)$, we denoted $\deg_S(v)$, for the number of neighbors of v in S . We write P_n for the *path* of order n , C_n for the *cycle* of length n and K_n for the complete graph of order n . For two disjoint subsets S and T of $V(G)$, we write $[S, T]$ for the set of edges of G joining S to T . If K is a subset of $\mathbb{Z}$ and f is a function from $V(G)$ into K , then we write $V_i = \{v \in V(G) \mid f(v) = i\}$ for each $i \in K$.

In 2016, Beeler et al. [10] defined the double Roman domination as follows. A function $f : V \rightarrow \{0, 1, 2, 3\}$ is a *double Roman dominating function* (DRDF) on a graph G if the following conditions hold.

- (i) If $f(v) = 0$, then v must have at least one neighbor in V_3 or at least two neighbors in V_2 .
- (ii) If $f(v) = 1$, then v must have at least one neighbor in $V_2 \cup V_3$.

The *double Roman domination number* $\gamma_{dR}(G)$ equals the minimum weight of a double Roman dominating function on G . The double Roman domination has been studied by several authors [1, 2, 4, 5]. For further results on several new variations of Roman domination see [6, 7, 8, 11, 14].

Amjadi et al. [9], introduced a new variation of double Roman domination as signed double Roman k -domination number. A *signed double Roman k -dominating function* (SDRkDF) on a graph $G = (V, E)$ is a function $f : V(G) \rightarrow \{-1, 1, 2, 3\}$ such that (i) every vertex v with $f(v) = -1$ is adjacent to at least two vertices assigned a 2 or to at least one vertex w with $f(w) = 3$, (ii) every vertex v with $f(v) = 1$ is adjacent to at least one vertex w with $f(w) \geq 2$ and (iii) $f(v) = \sum_{u \in N[v]} f(u) \geq k$ holds for any vertex v . The weight of an SDRkDF f is the value $\omega(f) = \sum_{u \in V(G)} f(u)$. The *signed double Roman k -domination number* $\gamma_{sdR}^k(G)$ is the minimum weight of an SDRkDF on G . For further results on signed double Roman k -domination see [7, 16].

A *signed total double Roman k -dominating function* (STDRkDF) on a graph $G = (V, E)$ is a function $f : V(G) \rightarrow \{-1, 1, 2, 3\}$ such that (i) every vertex v with $f(v) = -1$ is adjacent to at least two vertices assigned a 2 or to at least one vertex w with $f(w) = 3$, (ii) every vertex v with $f(v) = 1$ is adjacent to at least one vertex w with $f(w) \geq 2$ and (iii) $f(v) = \sum_{u \in N(v)} f(u) \geq k$ holds for

any vertex v . The weight of an STDRkDF f is the value $\omega(f) = \sum_{u \in V(G)} f(u)$. The *signed total double Roman k -domination number* $\gamma_{stdR}^k(G)$ is the minimum weight of an STDRkDF on G . For an STDRkDF f , let $V_i(f) = \{v \in V \mid f(v) = i\}$. In the context of a fixed STDRkDF, we suppress the argument and simply write V_{-1} , V_1 , V_2 and V_3 . Since this partition determines f , we can equivalently write $f = (V_{-1}, V_1, V_2, V_3)$. The concept of signed total double Roman k -domination was introduced and investigated by Shahbazi et al. [12]. The special case $k = 1$ is the usual signed total double Roman domination which has been investigated in [13]. Shahbazi et al. [13] proved that for any connected graph G of order $n \geq 3$ and size m , $\gamma_{stdR}^t(G) \geq \frac{11n-12m}{3}$.

Following the same idea, in this paper we present sharp lower bounds for $\gamma_{stdR}^2(G)$ and $\gamma_{stdR}^3(G)$ in terms of the order and the size of the graph G .

We make use of the following results in this paper.

Proposition A. [12] For $n \geq 2$,

$$\gamma_{stdR}^2(P_n) = \begin{cases} 4 & \text{if } n = 2, 3 \\ n & \text{if } n \equiv 0 \pmod{4} \\ n + 2 & \text{if } n \equiv 1, 3 \pmod{4} \\ n + 3 & \text{if } n \equiv 2 \pmod{4}. \end{cases}$$

Proposition B. [12] For $n \geq 2$,

$$\gamma_{stdR}^3(P_n) = \begin{cases} \frac{3n}{2} + 3 & \text{if } n \equiv 2 \pmod{4} \\ \lceil \frac{3n}{2} \rceil + 2 & \text{otherwise.} \end{cases}$$

Proposition C. [12] For $n \geq 3$,

$$\gamma_{stdR}^2(C_n) = \begin{cases} 4 & \text{if } n = 3 \\ n & \text{if } n \equiv 0 \pmod{4} \\ n + 2 & \text{if } n = 6, n \equiv 1 \text{ or } 3 \pmod{4} \text{ and } n \neq 3 \\ n + 4 & \text{if } n \equiv 2 \pmod{4}. \end{cases}$$

Proposition D. [12] If $n \geq 3$, then

$$\gamma_{stdR}^3(C_n) = \begin{cases} \lceil \frac{3n}{2} \rceil + 1 & \text{if } n \equiv 2 \pmod{4} \\ \lceil \frac{3n}{2} \rceil & \text{otherwise.} \end{cases}$$

Proposition E. [12] For $k \geq 2$ and $n \geq \lceil \frac{k}{2} \rceil + 1$, $\gamma_{stdR}^k(K_n) = k + 2$.

We close this section with two simple results.

Lemma 1.1. If G is a connected graph of order 4 and size m , then $\gamma_{stdR}^2(G) \geq \frac{92-24m}{5}$.

Proof. Let G be a connected graph of order 4. If $\Delta(G) = 2$, then $G \in \{P_4, C_4\}$ and the result follows from Propositions A and C. Assume that $\Delta(G) = 3$. If G is the complete graph K_4 , then the result follows from Proposition E. Suppose G is not the complete graph K_4 . Let $V(G) = \{v_1, v_2, v_3, v_4\}$, $\deg(v_1) = 3$ and

f be a $\gamma_{stdR}^2(G)$ -function. If v_i is a leaf for some $i \in \{2, 3, 4\}$, say $i = 2$, then we have

$$\begin{aligned}\gamma_{stdR}^2(G) &= \omega(f) \\ &= f(v_1) + f(N(v_1)) \\ &= f(N(v_2)) + f(N(v_1)) \\ &\geq 4 \\ &\geq \frac{92-24m}{5}.\end{aligned}$$

Hence, we assume that $\delta(G) \geq 2$. This implies that $m \geq 5$ and so

$$\begin{aligned}\gamma_{stdR}^2(G) &= \omega(f) \\ &= f(v_1) + f(N(v_1)) \\ &\geq f(v_1) + 2 \\ &\geq 1 \\ &> \frac{92-24m}{5}.\end{aligned}$$

□

2. LOWER BOUNDS ON $\gamma_{stdR}^2(G)$ AND $\gamma_{stdR}^3(G)$

In this section we provide sharp bounds on $\gamma_{stdR}^k(G)$ for $k = 2, 3$, in terms of the order and the size of G . To this end, we introduce some notation.

If $f = (V_{-1}, V_1, V_2, V_3)$ is an STDR k DF of G , then for notational convenience, we assume that $V'_{-1} = \{v \in V_{-1} \mid N(v) \cap V_3 \neq \emptyset\}$ and $V''_{-1} = V_{-1} - V'_{-1}$. Also, we let $V_{12} = V_1 \cup V_2$, $V_{13} = V_1 \cup V_3$, $V_{123} = V_1 \cup V_2 \cup V_3$, $|V_{12}| = n_{12}$, $|V_{13}| = n_{13}$, $|V_{123}| = n_{123}$, $|V_1| = n_1$, $|V_2| = n_2$, $|V_3| = n_3$ and $|V_{-1}| = n_{-1}$. Then $n_{123} = n_1 + n_2 + n_3$ and $n_{-1} = n - n_{123}$. Let $G_{123} = G[V_{123}]$ be the subgraph induced by the set V_{123} and let G_{123} have size m_{123} . For $i = 1, 2, 3$, if $V_i \neq \emptyset$, let $G_i = G[V_i]$ be the subgraph induced by the set V_i and let G_i have size m_i . Hence, $m_{123} = m_1 + m_2 + m_3 + |[V_1, V_2]| + |[V_1, V_3]| + |[V_2, V_3]|$.

Theorem 2.1. *Let G be a connected graph of order $n \geq 4$ and size m . Then*

$$\gamma_{stdR}^2(G) \geq \frac{23n - 24m}{5}.$$

Proof. Let $f = (V_{-1}, V_1, V_2, V_3)$ be a $\gamma_{stdR}^3(G)$ -function such that (i) $|V_3|$ is maximized and (ii) subject to (i), $|V_3 \cap L|$ is minimized where $L = \{v \in V(G) \mid \deg(v) = 1\}$. The result is immediate for $n = 4$ by Lemma 1.1. Assume that $n \geq 5$.

If $V_{-1} = \emptyset$, then clearly $\gamma_{stdR}^2(G) \geq n + 1 \geq \frac{23n-24m}{5}$ since $n \geq 5$ and $m \geq n - 1$. Henceforth, we assume $V_{-1} \neq \emptyset$. We consider the following cases.

Case 1. $V_3 \neq \emptyset$.

We distinguish the following situation.

Subcase 1.1. $V_2 \neq \emptyset$.

Since each vertex in V_{-1} is adjacent to at least one vertex in V_3 or to at least

two vertices in V_2 , we have

$$|[V_{-1}, V_3]| + |[V_{-1}, V_2]| \geq |V'_{-1}| + 2|V''_{-1}| \geq |V'_{-1}| + |V''_{-1}| \geq n_{-1}.$$

Furthermore we have

$$2n_{-1} = 2|V'_{-1}| + 2|V''_{-1}| \leq 2|[V_{-1}, V_3]| + |[V_{-1}, V_2]| = 2 \sum_{v \in V_3} \deg_{V_{-1}}(v) + \sum_{u \in V_2} \deg_{V_{-1}}(u).$$

For each vertex $v \in V_2 \cup V_3$, we have that $3 \deg_{V_3}(v) + 2 \deg_{V_2}(v) + \deg_{V_1}(v) - \deg_{V_{-1}}(v) = f(N(v)) \geq 2$, and so

$$\deg_{V_{-1}}(v) \leq 3 \deg_{V_3}(v) + 2 \deg_{V_2}(v) + \deg_{V_1}(v) - 2.$$

Now, we have

$$\begin{aligned} 2n_{-1} &\leq 2 \sum_{v \in V_3} \deg_{V_{-1}}(v) + \sum_{u \in V_2} \deg_{V_{-1}}(u) \\ &\leq 2 \sum_{v \in V_3} (3 \deg_{V_3}(v) + 2 \deg_{V_2}(v) + \deg_{V_1}(v) - 2) \\ &\quad + \sum_{u \in V_2} (3 \deg_{V_3}(u) + 2 \deg_{V_2}(u) + \deg_{V_1}(u) - 2) \\ &= (12m_3 + 4|[V_2, V_3]| + 2|[V_1, V_3]| - 4n_3) + (3|[V_2, V_3]| + 4m_2 + |[V_1, V_2]| - 2n_2) \\ &= 12m_3 + 4m_2 + 7|[V_2, V_3]| + 2|[V_1, V_3]| + |[V_1, V_2]| - 4n_3 - 2n_2 \\ &= 12m_{123} - 12m_1 - 8m_2 - 5|[V_2, V_3]| - 10|[V_1, V_3]| - 11|[V_1, V_2]| - 4n_3 - 2n_2, \end{aligned}$$

and this implies that

$$m_{123} \geq \frac{1}{12}(2n_{-1} + 12m_1 + 8m_2 + 5|[V_2, V_3]| + 10|[V_1, V_3]| + 11|[V_1, V_2]| + 4n_3 + 2n_2).$$

Therefore,

$$\begin{aligned} m &\geq m_{123} + |[V_{-1}, V_{123}]| + m_{-1} \\ &\geq m_{123} + |[V_{-1}, V_{123}]| \\ &\geq \frac{1}{12}(2n_{-1} + 12m_1 + 8m_2 + 5|[V_2, V_3]| + 10|[V_1, V_3]| + 11|[V_1, V_2]| + 4n_3 + 2n_2) \\ &\quad + |[V_{-1}, V_1]| + n_{-1} \\ &= \frac{1}{12}(14n_{-1} + 4n_{123} - 4n_1 - 2n_2 + 12m_1 + 8m_2 + 5|[V_2, V_3]| + 10|[V_1, V_3]| \\ &\quad + 11|[V_1, V_2]| + 12|[V_{-1}, V_1]|) \\ &= \frac{1}{12}(14n - 10n_{123} - 4n_1 - 2n_2 + 12m_1 + 8m_2 + 5|[V_2, V_3]| + 10|[V_1, V_3]| \\ &\quad + 11|[V_1, V_2]| + 12|[V_{-1}, V_1]|), \end{aligned}$$

and so

$$\begin{aligned} n_{123} &\geq \frac{1}{10}(-12m + 14n - 4n_1 - 2n_2 + 12m_1 + 8m_2 + 5|[V_2, V_3]| \\ &\quad + 10|[V_1, V_3]| + 11|[V_1, V_2]| + 12|[V_{-1}, V_1]|). \end{aligned}$$

Now, we have

$$\begin{aligned}
 \gamma_{stdR}^2(G) &= 3n_3 + 2n_2 + n_1 - n_{-1} \\
 &= 4n_3 + 3n_2 + 2n_1 - n \\
 &= 4n_{123} - n - n_2 - 2n_1 \\
 &\geq \frac{4}{10}(-12m + 14n - 4n_1 - 2n_2 + 12m_1 + 8m_2 + 5|[V_2, V_3]| \\
 &\quad + 10|[V_1, V_3]| + 11|[V_1, V_2]| + 12|[V_{-1}, V_1]|) - n - n_2 - 2n_1 \\
 &= \frac{2}{5}\left(\frac{23n}{2} - \frac{24m}{2}\right) + \frac{2}{5}\left(-9n_1 - \frac{9}{2}n_2 + 12m_1 + 8m_2 + 5|[V_2, V_3]| \right. \\
 &\quad \left. + 10|[V_1, V_3]| + 11|[V_1, V_2]| + 12|[V_{-1}, V_1]|)\right).
 \end{aligned}$$

Let $\Theta = -9n_1 - \frac{9}{2}n_2 + 12m_1 + 8m_2 + 5|[V_2, V_3]| + 10|[V_1, V_3]| + 11|[V_1, V_2]| + 12|[V_{-1}, V_1]|$. We show that $\Theta \geq 0$. First let $n_1 = 0$, then $\Theta = -\frac{9}{2}n_2 + 8m_2 + 5|[V_2, V_3]|$. Let V_2^1 be the set of vertices with label 2 having a neighbor in V_3 , V_2^2 be the subset of $V_2 - V_2^1$ with label 2 having a neighbor in V_2^1 , V_2^3 be the subset of $V_2 - (V_2^1 \cup V_2^2)$ and etc. Since any vertex in V_2 have a neighbor in $V_3 \cup V_2$, by repeating this process we obtain a partition $V_2^1 \cup V_2^2 \cup \dots \cup V_2^r$ of V_2 such that each vertex in V_2^i has a neighbor in V_2^{i-1} for each $2 \leq i \leq r-1$ and that $N(x) \cap V_2 \subseteq V_2^r$ for each $x \in V_2^r$. We claim that each vertex $v \in V_2^r$ has at least two neighbors in V_2^r . Suppose, to the contrary, that there exists a vertex $v \in V_2^r$ having exactly one neighbor u in V_2^r . Then $\deg_G(v) = 1$ and since G is connected and f is an STD2DF of G we deduce that u has a neighbor in $V_2^r - \{v\}$. But then the function g defined on G by $g(v) = 1, g(u) = 3$ and $g(x) = f(x)$ otherwise, is a $\gamma_{stdR}^2(G)$ -function which contradicts the choice of f . Hence each vertex $v \in V_2^r$ has at least two neighbors in V_2^r . Then

$$\begin{aligned}
 \Theta &= -\frac{9}{2}n_2 + 8m_2 + 5|[V_2, V_3]| \\
 &\geq -\frac{9}{2}n_2 + 5|[V_2^1, V_3]| + 8\left(\sum_{i=2}^{r-1} |[V_2^i, V_2^{i-1}]| \right) + 8|E(G[V_2^r])| \\
 &\geq -\frac{9}{2}n_2 + 5|V_2^1| + 8\left(\sum_{i=2}^{r-1} |V_2^i| \right) + 8|V_2^r| \\
 &\geq -\frac{9}{2}n_2 + 5|V_2| \\
 &> 0.
 \end{aligned}$$

Therefore $\gamma_{stdR}^2(G) > \frac{23n-24m}{5}$. Suppose now that $n_1 \geq 1$. Let V_1^1 be the set of vertices with label 1 having a neighbor in V_3 and V_2^1 be the set of vertices with label 2 having a neighbor in $V_3 \cup V_1^1$. Suppose V_1^2 is the subset of $V_1 - V_1^1$ having a neighbor in $V_1^1 \cup V_2^1$ and V_2^2 is the subset of $V_2 - V_2^1$ having a neighbor in $V_1^2 \cup V_2^1$. Since V_1 and V_2 are finite sets, by repeating this process we obtain disjoint subsets $V_1^1 \cup V_1^2 \cup \dots \cup V_1^r$ of V_1 (possibly some of V_1^i are empty) such

that each vertex in V_1^i has a neighbor in $V_1^{i-1} \cup V_2^{i-1}$ for each $2 \leq i \leq r$, and disjoint subsets $V_2^1 \cup V_2^2 \cup \dots \cup V_2^r$ of V_2 (possibly some of V_2^i are empty) so that every vertex in V_2^i has a neighbor in $V_1^i \cup V_2^{i-1}$ for each $2 \leq i \leq r$ and that $V_1^r = V_2^r = \emptyset$. Let $V_1^{r+1} = V_1 - (\cup_{i=1}^r V_1^i)$ and $V_2^{r+1} = V_2 - (\cup_{i=1}^r V_2^i)$. Clearly, $V_1^1 \cup V_1^2 \cup \dots \cup V_1^{r+1}$ is a weak partition of V_1 and $V_2^1 \cup V_2^2 \cup \dots \cup V_2^{r+1}$ is a weak partition of V_2 . Note that $N(x) \subseteq V_1^{r+1} \cup V_2^{r+1} \cup V_{-1}$ for each $x \in V_1^{r+1} \cup V_2^{r+1}$. Assume that $H_1, \dots, H_t$ be the components of $G[V_1^{r+1} \cup V_2^{r+1}]$. Since G is connected and f is a STDR2DF of G , we must have $|V(H_i)| \geq 3$ for each $1 \leq i \leq t$, if $V_1^{r+1} \cup V_2^{r+1} \neq \emptyset$. Then

$$\begin{aligned} \Theta &= -9n_1 - \frac{9}{2}n_2 + 12m_1 + 8m_2 + 5|[V_2, V_3]| + 10|[V_1, V_3]| + 11|[V_1, V_2]| + 12|[V_{-1}, V_1]| \\ &\geq (-9|V_1^1| + 10|[V_1^1, V_3]|) + \sum_{i=2}^r \left(-9|V_1^i| + 12|[V_1^i, V_1^{i-1}]| + 11|[V_1^i, V_2^{i-1}]| \right) + \\ &\quad \left(-\frac{9}{2}|V_2^1| + 5|[V_2^1, V_3]| + 11|[V_1^1, V_2^1]| \right) \\ &\quad + \sum_{i=2}^r \left(-\frac{9}{2}|V_2^i| + 8|[V_2^i, V_2^{i-1}]| + 11|[V_1^i, V_2^i]| \right) + \sum_{i=1}^t \left(-\frac{9}{2}n(H_i) + 8m(H_i) \right) \\ &\geq \sum_{i=1}^t \left(-\frac{9}{2}n(H_i) + 8(n(H_i) - 1) \right) \\ &\geq \sum_{i=1}^t \left(\frac{7}{2}n(H_i) - 8 \right) \\ &> 0. \end{aligned}$$

Therefore $\gamma_{stdR}^2(G) > \frac{23n-24m}{5}$.

Subcase 1.2. $V_2 = \emptyset$.

By definition of STDR2DF, each vertex in V_{-1} is adjacent to one vertex in V_3 , and so

$$\sum_{v \in V_3} \deg_{V_{-1}}(v) = |[V_{-1}, V_3]| \geq |V_{-1}| = n_{-1}.$$

As in Subcase 1.1, for each $v \in V_3$ we have $3\deg_{V_3}(v) + \deg_{V_1}(v) - \deg_{V_{-1}}(v) = f(N(v)) \geq 2$, and so $\deg_{V_{-1}}(v) \leq 3\deg_{V_3}(v) + \deg_{V_1}(v) - 2$. Now, we have

$$\begin{aligned} n_{-1} &\leq \sum_{v \in V_3} \deg_{V_{-1}}(v) \\ &\leq \sum_{v \in V_3} (3\deg_{V_3}(v) + \deg_{V_1}(v) - 2) \\ &= 6m_3 + |[V_1, V_3]| - 2n_3 \\ &= 6m_{13} - 6m_1 - 5|[V_1, V_3]| - 2n_3, \end{aligned}$$

which implies that $m_{13} \geq \frac{1}{6}(n_{-1} + 6m_1 + 5|[V_1, V_3]| + 2n_3)$. Hence,

$$\begin{aligned}
 m &= m_{13} + |[V_{-1}, V_3]| + |[V_{-1}, V_1]| + m_{-1} \\
 &\geq m_{13} + |[V_{-1}, V_3]| + |[V_{-1}, V_1]| \\
 &\geq \frac{1}{6}(n_{-1} + 6m_1 + 5|[V_1, V_2]| + 2n_3) + n_{-1} + |[V_{-1}, V_1]| \\
 &= \frac{1}{6}(7n_{-1} + 2n_3 + 6m_1 + 5|[V_1, V_3]| + 6|[V_{-1}, V_1]|) \\
 &= \frac{1}{6}(7n_{-1} + 2n_{13} - 2n_1 + 6m_1 + 5|[V_1, V_3]| + 6|[V_{-1}, V_1]|) \\
 &= \frac{1}{6}(7n - 5n_{13} - 2n_1 + 6m_1 + 5|[V_1, V_3]| + 6|[V_{-1}, V_1]|),
 \end{aligned}$$

and so

$$n_{13} \geq \frac{1}{5}(-6m + 7n - 2n_1 + 6m_1 + 5|[V_1, V_3]| + 6|[V_{-1}, V_1]|).$$

Now, we have

$$\begin{aligned}
 \gamma_{stdR}^2(G) &= 3n_3 + n_1 - n_{-1} \\
 &= 4n_3 + 2n_1 - n \\
 &= 4n_{13} - n - 2n_1 \\
 &\geq \frac{4}{5}(-6m + 7n - 2n_1 + 6m_1 + 5|[V_1, V_3]| + 6|[V_{-1}, V_1]|) - n - 2n_1 \\
 &= \frac{4}{5}(-6m + 7n - \frac{5}{4}n - 2n_1 - \frac{5}{2}n_1 + 6m_1 + 5|[V_1, V_3]| + 6|[V_{-1}, V_1]|) \\
 &= \frac{4}{5}(\frac{23}{4}n - 6m) + \frac{4}{5}(-\frac{9}{2}n_1 + 6m_1 + 5|[V_1, V_3]| + 6|[V_{-1}, V_1]|).
 \end{aligned}$$

Let $\Theta = -\frac{9}{2}n_1 + 6m_1 + 5|[V_1, V_3]| + 6|[V_{-1}, V_1]|$. We show that $\Theta \geq 0$. If $n_1 = 0$, then $\Theta = 0$. Suppose that $n_1 \geq 1$. Since each vertex of V_1 is adjacent to a vertex of V_3 , we have $|[V_1, V_3]| \geq n_1$. It follows that

$$\begin{aligned}
 \Theta &= -\frac{9}{2}n_1 + 6m_1 + 5|[V_1, V_3]| + 6|[V_{-1}, V_1]| \\
 &\geq -\frac{9}{2}n_1 + 6m_1 + 5n_1 + 6|[V_{-1}, V_1]| \\
 &> 0.
 \end{aligned}$$

Therefore $\gamma_{stdR}^2(G) > \frac{23n-24m}{5}$.

Case 2. $V_3 = \emptyset$.

Since $V_{-1} \neq \emptyset$, we conclude that $V_2 \neq \emptyset$. By definition of STDR2DF, each vertex in V_{-1} is adjacent to at least two vertices in V_2 , and so

$$\sum_{v \in V_2} \deg_{V_{-1}}(v) = |[V_{-1}, V_2]| \geq 2|V_{-1}| = 2n_{-1}.$$

As in Subcase 1.1, for each $v \in V_2$ we have that $2\deg_{V_2}(v) + \deg_{V_1}(v) - \deg_{V_{-1}}(v) = f(N(v)) \geq 2$, and so $\deg_{V_{-1}}(v) \leq 2\deg_{V_2}(v) + \deg_{V_1}(v) - 2$.

Now, we have

$$\begin{aligned}
 2n_{-1} &\leq \sum_{v \in V_2} \deg_{V_{-1}}(v) \\
 &\leq \sum_{v \in V_2} (2 \deg_{V_2}(v) + \deg_{V_1}(v) - 2) \\
 &= 4m_2 + |[V_1, V_2]| - 2n_2 \\
 &= 4m_{12} - 4m_1 - 3|[V_1, V_2]| - 2n_2,
 \end{aligned}$$

which implies that

$$m_{12} \geq \frac{1}{4}(2n_{-1} + 4m_1 + 3|[V_1, V_2]| + 2n_2).$$

Hence,

$$\begin{aligned}
 m &= m_{12} + |[V_{-1}, V_{12}]| + m_{-1} \\
 &\geq m_{12} + |[V_{-1}, V_{12}]| \\
 &\geq \frac{1}{4}(2n_{-1} + 4m_1 + 3|[V_1, V_2]| + 2n_2) + 2n_{-1} + |[V_1, V_{-1}]| \\
 &= \frac{1}{4}(10n_{-1} + 2n_{12} - 2n_1 + 4m_1 + 3|[V_1, V_2]| + 4|[V_1, V_{-1}]|) \\
 &= \frac{1}{4}(10n - 8n_{12} - 2n_1 + 4m_1 + 3|[V_1, V_2]| + 4|[V_1, V_{-1}]|)
 \end{aligned}$$

and so $n_{12} \geq \frac{1}{8}(-4m + 10n - 2n_1 + 4m_1 + 3|[V_1, V_2]| + 4|[V_1, V_{-1}]|)$. Now, we have

$$\begin{aligned}
 \gamma_{stdR}^2(G) &= 2n_2 + n_1 - n_{-1} \\
 &= 3n_2 + 2n_1 - n \\
 &= 3n_{12} - n - n_1 \\
 &\geq \frac{3}{8}(-4m + 10n - 2n_1 + 4m_1 + 3|[V_1, V_2]| + 4|[V_1, V_{-1}]|) - n - n_1 \\
 &= \frac{3}{8}(-4m + 10n - \frac{8}{3}n) + \frac{3}{8}(-\frac{14}{3}n_1 + 4m_1 + 3|[V_1, V_2]| \\
 &\quad + 4|[V_1, V_{-1}]|) \\
 &\geq \frac{3}{8}(-4m + \frac{22}{3}n) - \frac{5}{8}m + \frac{5}{8}m + \frac{3}{8}(-\frac{14}{3}n_1 + 4m_1 + 3|[V_1, V_2]| \\
 &\quad + 4|[V_1, V_{-1}]|) \\
 &= \frac{1}{8}(-17m + 22n) + \frac{3}{8}(-\frac{14}{3}n_1 + 4m_1 + \frac{5}{3}m + 3|[V_1, V_2]| \\
 &\quad + 4|[V_1, V_{-1}]|).
 \end{aligned}$$

Let $\Theta = -\frac{14}{3}n_1 + 4m_1 + \frac{5}{3}m + 3|[V_1, V_2]| + 4|[V_1, V_{-1}]|$. If $n_1 = 0$, then $\Theta > 0$. Suppose that $n_1 \geq 1$. Since any vertex in V_1 is adjacent to a vertex in V_2 , we have

$$\begin{aligned}\Theta &= -\frac{14}{3}n_1 + 4m_1 + \frac{5}{3}m + 3|[V_1, V_2]| + 4|[V_1, V_{-1}]| \\ &\geq -\frac{14}{3}n_1 + \frac{17}{3}m_1 + \frac{14}{3}|[V_1, V_2]| \\ &\geq 0\end{aligned}$$

Therefore $\gamma_{stdR}^2(G) \geq \frac{1}{8}(22n - 17m) > \frac{1}{5}(23n - 24m)$. This completes the proof. $\square$

In the next example, we present an infinite family of graphs that attain the bound of Theorem 2.1.

EXAMPLE 2.2. For any connected graph F of order $t \geq 2$, let F_t be the graph obtained from F by adding $3 \deg_F(v) - 2$ pendant edges to each vertex v of F . Then

$$n(F_t) = n(F) + \sum_{v \in V(F)} (3 \deg_F(v) - 2) = 6m(F) - n(F)$$

and

$$m(F_t) = m(F) + \sum_{v \in V(F)} (3 \deg_F(v) - 2) = 7m(F) - 2n(F).$$

Assigning a 3 to every vertex in $V(F)$ and a -1 to every vertex in $V(F_t) - V(F)$ produces an STDR2DF of weight

$$3n(F) - \sum_{v \in V(F)} (3 \deg_F(v) - 2) = 5n(F) - 6m(F) = \frac{23n(F_t) - 24m(F_t)}{5},$$

and so $\gamma_{stdR}^2(F_t) \leq \frac{23n(F_t) - 24m(F_t)}{5}$. Applying Theorem 2.1, we have $\gamma_{stdR}^2(F_t) = \frac{23n(F_t) - 24m(F_t)}{5}$.

Next we present a sharp lower bound on $\gamma_{stdR}^3(G)$.

Theorem 2.3. *Let G be a connected graph of order $n \geq 5$ and size m . Then*

$$\gamma_{stdR}^3(G) \geq 6n - 6m.$$

Furthermore, this bound is sharp.

Proof. Let $f = (V_{-1}, V_1, V_2, V_3)$ be a $\gamma_{stdR}^2(G)$ -function such that (i) $|V_3|$ is maximized and (ii) subject to (i), $|V_3 \cap L|$ is minimized where $L = \{v \in V(G) \mid \deg(v) = 1\}$. If $V_{-1} = \emptyset$, then $\gamma_{stdR}^3(G) \geq n + 1 > 6n - 6m$. Suppose that $V_{-1} \neq \emptyset$. Consider the following cases.

Case 1. $V_3 \neq \emptyset$.

First let $V_2 \neq \emptyset$. As in the proof of Theorem 2.1, we have

$$\sum_{v \in V_3} \deg_{V_{-1}}(v) + \frac{1}{2} \sum_{u \in V_2} \deg_{V_{-1}}(u) = |[V_{-1}, V_3]| + \frac{1}{2} |[V_{-1}, V_2]| \geq |V'_{-1}| + |V''_{-1}| = n_{-1},$$

and for each vertex $v \in V_2 \cup V_3$, $\deg_{V_{-1}}(v) \leq 3 \deg_{V_3}(v) + 2 \deg_{V_2}(v) + \deg_{V_1}(v) - 3$. Now, we have

$$\begin{aligned}
3n_{-1} &\leq 3 \sum_{v \in V_3} \deg_{V_{-1}}(v) + \frac{3}{2} \sum_{u \in V_2} \deg_{V_{-1}}(u) \\
&\leq 3 \sum_{v \in V_3} (3 \deg_{V_3}(v) + 2 \deg_{V_2}(v) + \deg_{V_1}(v) - 3) \\
&\quad + \frac{3}{2} \sum_{u \in V_2} (3 \deg_{V_3}(u) + 2 \deg_{V_2}(u) + \deg_{V_1}(u) - 3) \\
&= (18m_3 + 6|[V_2, V_3]| + 3|[V_1, V_3]| - 9n_3) + \left(\frac{9}{2}[|V_2, V_3]| + 6m_2 + \frac{3}{2}[|V_1, V_2]| - \frac{9}{2}n_2\right) \\
&= 18m_3 + 6m_2 + \frac{21}{2}[|V_2, V_3]| + 3|[V_1, V_3]| + \frac{3}{2}[|V_1, V_2]| - 9n_3 - \frac{9}{2}n_2 \\
&= 18m_{123} - 18m_1 - 12m_2 - \frac{15}{2}[|V_2, V_3]| - 15|[V_1, V_3]| - \frac{33}{2}[|V_1, V_2]| - 9n_3 - \frac{9}{2}n_2,
\end{aligned}$$

and so

$$m_{123} \geq \frac{1}{18}(3n_{-1} + 18m_1 + 12m_2 + \frac{15}{2}[|V_2, V_3]| + 15|[V_1, V_3]| + \frac{33}{2}[|V_1, V_2]| + 9n_3 + \frac{9}{2}n_2).$$

Using an argument similar to that described in the proof of Theorem 2.1, we obtain

$$\begin{aligned}
n_{123} &\geq \frac{1}{12}(-18m + 21n - 9n_1 - \frac{9}{2}n_2 + 18m_1 + 12m_2 + \frac{15}{2}[|V_2, V_3]| + 15|[V_1, V_3]| \\
&\quad + \frac{33}{2}[|V_1, V_2]| + 18|[V_{-1}, V_1]|).
\end{aligned}$$

Now, we have

$$\begin{aligned}
\gamma_{stdR}^3(G) &= 3n_3 + 2n_2 + n_1 - n_{-1} \\
&= 4n_3 + 3n_2 + 2n_1 - n \\
&= 4n_{123} - n - n_2 - 2n_1 \\
&\geq \frac{4}{12}(-18m + 21n - 9n_1 - \frac{9}{2}n_2 + 18m_1 + 12m_2 + \frac{15}{2}[|V_2, V_3]| \\
&\quad + 15|[V_1, V_3]| + \frac{33}{2}[|V_1, V_2]| + 18|[V_{-1}, V_1]|) - n - n_2 - 2n_1 \\
&= \frac{1}{3}(-18m + 18n - 15n_1 - \frac{15}{2}n_2 + 18m_1 + 12m_2 + \frac{15}{2}[|V_2, V_3]| \\
&\quad + 15|[V_1, V_3]| + \frac{33}{2}[|V_1, V_2]| + 18|[V_{-1}, V_1]|) \\
&= 6n - 6m + \frac{1}{3}(-15n_1 - \frac{15}{2}n_2 + 18m_1 + 12m_2 + \frac{15}{2}[|V_2, V_3]| \\
&\quad + 15|[V_1, V_3]| + \frac{33}{2}[|V_1, V_2]| + 18|[V_{-1}, V_1]|).
\end{aligned}$$

Let $\Theta = -15n_1 - \frac{15}{2}n_2 + 18m_1 + 12m_2 + \frac{15}{2}[|V_2, V_3]| + 15|[V_1, V_3]| + \frac{33}{2}[|V_1, V_2]| + 18|[V_{-1}, V_1]|$. We show that $\Theta \geq 0$. If $n_1 = 0$, then $\Theta = -\frac{15}{2}n_2 + 12m_2 + \frac{15}{2}[|V_2, V_3]|$ and as in the proof of Theorem 2.1 we can see that $\Theta > 0$ implying that $\gamma_{sdR}^t(G) > 6n - 6m$. Suppose now that $n_1 \geq 1$.

Now we use the notations defined in the proof of Theorem 2.1 (Subcase 1.1). Since G is connected and f is a STDR3DF of G , we must have $|V(H_i)| \geq 3$

and $\delta(H_i) \geq 2$ for each $1 \leq i \leq t$. It follows that $|E(H_i)| \geq |V(H_i)|$ for each $1 \leq i \leq t$. Thus

$$\begin{aligned}
 \Theta &= -15n_1 - \frac{15}{2}n_2 + 18m_1 + 12m_2 + \frac{15}{2}||[V_2, V_3]| + 15|[V_1, V_3]| \\
 &\quad + \frac{33}{2}||[V_1, V_2]| + 18|[V_{-1}, V_1]| \\
 &\geq (-15|V_1^1| + 15|[V_1^1, V_3]|) + \sum_{i=2}^r \left(-15|V_1^i| + 18|[V_1^i, V_1^{i-1}]| + \frac{33}{2}||[V_1^i, V_2^{i-1}]| \right) \\
 &\quad + \left(-\frac{15}{2}|V_2^1| + \frac{15}{2}||[V_2^1, V_3]| + \frac{33}{2}||[V_1^1, V_2^1]| \right) \\
 &\quad + \sum_{i=2}^{r+1} \left(-\frac{15}{2}|V_2^i| + 12|[V_2^i, V_2^{i-1}]| + \frac{33}{2}||[V_1^i, V_2^i]| \right) + \sum_{i=1}^t \left(-\frac{15}{2}n(H_i) + 12m(H_i) \right) \\
 &\geq \sum_{i=1}^t \left(-\frac{15}{2}n(H_i) + 12n(H_i) \right) \\
 &> 0.
 \end{aligned}$$

Therefore $\gamma_{stdR}^3(G) \geq 6n - 6m$.

Now let $V_2 = \emptyset$. As above, we have $\sum_{v \in V_3} \deg_{V_{-1}}(v) = |[V_{-1}, V_3]| \geq n_{-1}$ and $\deg_{V_{-1}}(v) \leq 3\deg_{V_3}(v) + \deg_{V_1}(v) - 3$ for each vertex $v \in V_3$. Now, we have

$$\begin{aligned}
 n_{-1} &\leq \sum_{v \in V_3} \deg_{V_{-1}}(v) \\
 &\leq \sum_{v \in V_3} (3\deg_{V_3}(v) + \deg_{V_1}(v) - 3) \\
 &= 6m_3 + |[V_1, V_3]| - 3n_3 \\
 &= 6m_{13} - 6m_1 - 5|[V_1, V_3]| - 3n_3,
 \end{aligned}$$

which implies that $m_{13} \geq \frac{1}{6}(n_{-1} + 6m_1 + 5|[V_1, V_3]| + 3n_3)$. Hence,

$$\begin{aligned}
 m &= m_{13} + |[V_{-1}, V_3]| + |[V_{-1}, V_1]| + m_{-1} \\
 &\geq m_{13} + |[V_{-1}, V_3]| + |[V_{-1}, V_1]| \\
 &\geq \frac{1}{6}(n_{-1} + 6m_1 + 5|[V_1, V_3]| + 3n_3) + n_{-1} + |[V_{-1}, V_1]| \\
 &= \frac{1}{6}(7n_{-1} + 3n_3 + 6m_1 + 5|[V_1, V_3]| + 6|[V_{-1}, V_1]|) \\
 &= \frac{1}{6}(7n_{-1} + 3n_{13} - 3n_1 + 6m_1 + 5|[V_1, V_3]| + 6|[V_{-1}, V_1]|) \\
 &= \frac{1}{6}(7n - 4n_{13} - 3n_1 + 6m_1 + 5|[V_1, V_3]| + 6|[V_{-1}, V_1]|)
 \end{aligned}$$

and this implies that

$$n_{13} \geq \frac{1}{4}(-6m + 7n - 3n_1 + 6m_1 + 5|[V_1, V_3]| + 6|[V_{-1}, V_1]|).$$

Now, we have

$$\begin{aligned}
 \gamma_{stdR}^3(G) &= 3n_3 + n_1 - n_{-1} \\
 &= 4n_3 + 2n_1 - n \\
 &= 4n_{13} - n - 2n_1 \\
 &\geq \frac{4}{4}(-6m + 7n - 3n_1 + 6m_1 + 5|[V_1, V_3]| + 6|[V_{-1}, V_1]|) - n - 2n_1 \\
 &= (-6m + 6n) + (-5n_1 + 6m_1 + 5|[V_1, V_3]| + 6|[V_{-1}, V_1]|) \\
 &> (-6m + 6n).
 \end{aligned}$$

Case 2. $V_3 = \emptyset$.

Since f is a STDR3DF of G , we conclude that $\delta(G) \geq 2$ and so $m \geq n$. Now $V_{-1} \neq \emptyset$ implies that $V_2 \neq \emptyset$. By definition of STDR3DF, each vertex in V_{-1} is adjacent to at least two vertices in V_2 , and so

$$|[V_{-1}, V_{12}]| \geq |[V_{-1}, V_2]| \geq 2|V_{-1}| = 2n_{-1}.$$

As above, we have $2n_{-1} \leq 4m_{12} - 4m_1 - 3|[V_1, V_2]| - 3n_2$ and hence

$$m_{12} \geq \frac{1}{4}(2n_{-1} + 4m_1 + 3|[V_1, V_2]| + 3n_2).$$

Now we have

$$\begin{aligned}
 m &= m_{12} + |[V_{-1}, V_{12}]| + m_{-1} \\
 &\geq m_{12} + |[V_{-1}, V_{12}]| \\
 &\geq \frac{1}{4}(2n_{-1} + 4m_1 + 3|[V_1, V_2]| + 3n_2) + 2n_{-1} + |[V_1, V_{-1}]| \\
 &\geq \frac{1}{4}(10n_{-1} + 3n_{12} + 4m_1 + 3|[V_1, V_2]| - 3n_1 + 4|[V_1, V_{-1}]|) \\
 &= \frac{1}{4}(10n - 7n_{12} + 4m_1 + 3|[V_1, V_2]| - 3n_1 + 4|[V_1, V_{-1}]|)
 \end{aligned}$$

and so

$$n_{12} \geq \frac{1}{7}(-4m + 10n + 4m_1 + 3|[V_1, V_2]| - 3n_1 + 4|[V_1, V_{-1}]|).$$

Thus

$$\begin{aligned}
 \gamma_{stdR}^3(G) &= 2n_2 + n_1 - n_{-1} \\
 &= 3n_2 + 2n_1 - n \\
 &= 3n_{12} - n - n_1 \\
 &\geq \frac{3}{7}(-4m + 10n + 4m_1 + 3|[V_1, V_2]| - 3n_1 + 4|[V_1, V_{-1}]|) - n - n_1 \\
 &= \frac{3}{7}(-4m + \frac{23}{3}n - \frac{16}{3}n_1 + 4m_1 + 3|[V_1, V_2]| + 4|[V_1, V_{-1}]|) \\
 &\geq \frac{3}{7}(-4m + \frac{23}{3}n) + \frac{3}{7}(-\frac{16}{3}n_1 + 4m_1 + 3|[V_1, V_2]| + 4|[V_1, V_{-1}]|) \\
 &= \frac{-12m + 23n}{7} + \frac{3}{7}(-\frac{16}{3}n_1 + 4m_1 + 3|[V_1, V_2]| + 4|[V_1, V_{-1}]|) \\
 &\geq \frac{-12m + 23n}{7} \\
 &> -6m + 6n.
 \end{aligned}$$

To prove the sharpness, let H_t ($t \geq 2$) be the graph obtained from a connected graph H of order t by adding $3 \deg_H(v) - 3$ pendant edges to each vertex v of H . Then

$$n(H_t) = n(H) + \sum_{v \in V(H)} (3 \deg_H(v) - 3) = 6m(H) - 2n(H)$$

and

$$m(H_t) = m(H) + \sum_{v \in V(H)} (3 \deg_H(v) - 3) = 7m(H) - 3n(H).$$

Assigning a 3 to every vertex in $V(H)$ and a -1 to every vertex in $V(H_t) - V(H)$ produces an STDR3DF f of weight

$$\omega(f) = 3n(H) - \sum_{v \in V(H)} (3 \deg_H(v) - 3) = 6n(H) - 6m(H) = 6n(H_t) - 6m(H_t),$$

and hence $\gamma_{stdR}^3(H_t) \leq 6n(H_t) - 6m(H_t)$. Thus $\gamma_{stdR}^3(H_t) = 6n(H_t) - 6m(H_t)$ and the proof is complete. $\square$

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