Relations on irredundance and domination number for six regular graph with girth 3

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Abstract
In this paper, we discuss about the irredundant number, upper irredundant number and domination number denoted by \( ir(G(n)) \), \( IR(G(n)) \) and \( \gamma(G(n)) \) respectively for 6-regular graphs of \( n \) vertices with girth 3. Here, \( G(n) \) denotes the 6-regular graphs on \( n \) vertices with girth 3. We further establish some relation between \( ir(G(n)) \), \( IR(G(n)) \) and \( \gamma(G(n)) \).

Keywords
6-regular graph, Girth, Irredundant set, Irredundant number, Dominating set, Domination number.

AMS Subject Classification
05C69.

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Article History
Received 05 March 2020; Accepted 11 May 2020 ©2020 MJM.

1. Introduction
Let \( G = (V, E) \) be a finite, undirected connected graph with neither loops nor multiple edges. For basic definitions and terminologies we refer to West [6]. The open neighbourhood of \( v \) is the set \( N(v) = \{ u \in V | uv \in E \} \) and the closed neighbourhood of \( v \) is \( N[v] = N(v) \cup \{ v \} \). A graph is called \( K \) regular if degree of each vertex in the graph is \( K \). The concept of domination was introduced by Ore [5]. A subset \( D \) of \( V(G) \) is a dominating set of \( G \) if every vertex in \( V - D \) is adjacent to at least one vertex in \( D \). The minimum cardinality among all dominating sets of \( G \) is called the domination number \( \gamma(G) \). Domination in graphs is well studied in [3, 4]. A set of vertices \( S \subseteq V(G) \) is an irredundant set if for every vertex \( v \in S \), there is a vertex \( u \in V(G) \) such that \( u \in N[S] \) but \( u \notin N[S - \{ v \}] \). \( v \) has its own private neighbour with respect to \( S \). An upper irredundant number \( IR(G) = \max\{|S| : S \text{ is an irredundant set}\} \). The maximum cardinality of \( S \) is upper irredundant number. The lower irredundant number \( \text{ir}(G) = \min\{|S| : S \text{ is a maximal irredundant set}\} \). The minimum cardinality of \( S \) is an lower irredundant number.

Irredundance concepts in graphs was defined by Cockayne in [1].

In [2], C. Jayasekaran and S. Delbin Prema has discussed about some exact results and relations between irredundance, upper irredundance and domination concepts for four regular graphs with girth 3. It stimulates to continue some other results among irredundance, upper irredundance and domination parameters for 6-regular graphs with girth 3. The structure of the 6-regular graphs with girth 3 is defined as follows.

Definition 1.1. If \( v_1 \) is adjacent with \( v_{n-2}, v_{n-1}, v_n, v_2, v_3, v_4; v_2 \) is adjacent with \( v_{n-1}, v_n, v_1, v_3, v_4, v_5; v_3 \) is adjacent with \( v_{n-1}, v_n, v_1, v_3, v_4, v_5; v_3 \) is adjacent with \( v_n, v_n, v_1, v_2, v_3, v_4, v_5 \); and \( v_1 \) is adjacent with \( v_{n-2}, v_{n-1}, v_n, v_2, v_3, v_4, v_5 \) such that \( v_1 v_2 \ldots v_n \) forms a cycle, then clearly each vertex is of degree 6. Hence, the graph has \( 3n \) edges. Thus, from the construction, we have a six regular graph of girth 3 with \( n \) vertices and \( 3n \) edges.

2. Exact values for \( ir(G(n)) \) and \( IR(G(n)) \)
In this section, we investigate some exact values among
irredundance and upper irredundance of graph $G(n)$.

**Theorem 2.3.** For the 6-regular graph with girth 3 and 7 vertices $G(7)$, there does not exist any irredundant set.

**Proof.** Suppose there exists an irredundant set $S$ for $G(7)$. Then for any vertex $v \in S$, $N[v] \neq N[S - v]$. Since $G(7) = K_7$, each vertex is adjacent to every other vertex in $G$. Therefore, $N[v] = V(G)$ and $N[S - v] = V(G)$ implies that $N[v] = N[S - v]$ which is a contradiction. Hence, there does not exist any irredundant set for $G(7)$.

**Observation 2.2.** In $G(n)$ there exists a redundant set only for $n = 7$.

**Proof.** Let $S \subseteq V(G)$ be a redundant set in $G(n)$. Then for any vertex $v \in S$, $N[v] = N[S - v]$. If $n \geq 8$, then by the Definition 2.1.1 for any graph $G(n)$, $N[v] \neq N[S - v]$, which is a contradiction. Therefore, $S$ is a redundant set only for $G(7)$.

**Theorem 2.3.** In $G(n), S = \{v_i, v_{i+7}, v_{i+14}, \ldots, v_{i + \left(\lfloor \frac{n}{7} \rfloor - 1 \right)7}\}$ is a minimum irredundant set for $1 \leq i \leq n$ and the suffixes modulo $n$.

**Proof.** Let $v_1, v_2, \ldots, v_n$ be the vertices of $G(n)$ such that $v_1v_2\ldots v_n$ forms a cycle. For an irredundant set $S$, we have $N[v] \neq N[S - v]$ where $v \in S$. By the construction of $G(n)$, starting with the vertex $v_1$ for $1 \leq i \leq n$, we have $N[v_i] = \{v_{i-3}, v_{i-2}, v_{i-1}, v_i, v_{i+1}, v_{i+2}, v_{i+3}\}$ where the suffixes modulo $n$ and $|N[v_i]| = 2$. Hence, the next vertex should be chosen as $v_{i+7}$, where $N[v_{i+7}] = \{v_{i+4}, v_{i+5}, v_{i+6}, v_{i+7}, v_{i+8}, v_{i+9}, v_{i+10}\}$. Clearly $N[v_i] \neq N[v_{i+7}]$. Proceeding like this, we can choose the minimum irredundant set as $\{v_1, v_{i+7}, v_{i+14}, \ldots, v_{i + \left(\lfloor \frac{n}{7} \rfloor - 1 \right)7}\}$ where the suffixes modulo $n$. Hence the proof.

**Example 2.4.** Consider the graph $G(13)$ given in figure 2.1. The minimum irredundant set are $\{v_1, v_8\}$, $\{v_2, v_9\}$, $\{v_3, v_{10}\}$, $\{v_4, v_{11}\}$, $\{v_5, v_{12}\}$, $\{v_6, v_{13}\}$, $\{v_7, v_1\}$, $\{v_8, v_2\}$, $\{v_9, v_3\}$, $\{v_{10}, v_4\}$, $\{v_{11}, v_5\}$, $\{v_{12}, v_6\}$ and $\{v_{13}, v_7\}$.

**Figure 2.2.** $G(14)$

**Case 2.** $m > 2$

The minimum irredundant set are $S_1 = \{v_1, v_{i+7}, \ldots, v_{i+n-7}\}$ where $1 \leq i \leq n$ and the suffixes modulo $n$. Here, $S_1 = \{v_1, v_8, \ldots, v_{n-6}\}$, $S_2 = \{v_2, v_9, \ldots, v_{n-5}\}$, $S_3 = \{v_3, v_{10}, \ldots, v_{n-4}\}$, $S_4 = \{v_4, v_{11}, \ldots, v_{n-3}\}$, $S_5 = \{v_5, v_{12}, \ldots, v_{n-2}\}$, $S_6 = \{v_6, v_{13}, \ldots, v_{n-1}\}$ and $S_7 = \{v_7, v_{14}, \ldots, v_n\}$. Proceeding like this we get $S_p = \{v_p, v_{p+7}, \ldots, v_{p+n-7}\}$ for $8 \leq p \leq n$. Since, the suffixes are modulo $n$ then $S_p$ is either $S_1$ or $S_2$ or $S_3$ or $S_4$ or $S_5$ or $S_6$ or $S_7$ according as $p \equiv 1 \pmod{7}$ or $p \equiv 2 \pmod{7}$ or $p \equiv 3 \pmod{7}$ or $p \equiv 4 \pmod{7}$ or $p \equiv 5 \pmod{7}$ or $p \equiv 6 \pmod{7}$ or $p \equiv 0 \pmod{7}$, respectively. Thus, $G(n)$ contains only 7 minimum irredundant sets.

**Example 2.6.** For $G(21)$ given in figure 2.3. The minimum irredundant set are $\{v_1, v_8, v_{15}\}$, $\{v_2, v_9, v_{16}\}$, $\{v_3, v_{10}, v_{17}\}$, $\{v_4, v_{11}, v_{18}\}$, $\{v_5, v_{12}, v_{19}\}$, $\{v_6, v_{13}, v_{20}\}$ and $\{v_7, v_{14}, v_{21}\}$. Thus, there are only 7 minimum irredundant set.
Theorem 2.7. In $G(n)$, $S' = \{v_1, v_1+4, v_1+8, \ldots, v_1+\left(\left\lceil \frac{n-1}{n} \right\rceil \right)\}$ is an upper irredundant set where $1 \leq i \leq n$ and the suffices modulo $n$.

Proof. Let $v_1, v_2, \ldots, v_n$ be the vertices of $G(n)$ such that $v_1 v_2 \ldots v_n v_1$ forms a cycle. Beginning with the vertex $v_i$ for $1 \leq i \leq n$ where $N[v_i] = \{v_{i-3}, v_{i-2}, v_{i-1}, v_i, v_{i+1}, v_{i+2}, v_{i+3}\}$, the suffices modulo $n$ and $|N[v_i]| = 7$. Since $N[v_i]$ contains the vertex $v_{i+3}$, the next vertex to be chosen is $v_{i+4}$ where $N[v_{i+4}] = \{v_{i+1}, v_{i+2}, v_{i+3}, v_{i+4}, v_{i+5}, v_{i+6}, v_{i+7}\}$. Clearly, $N[v_i] \neq N[v_{i+4}]$. Now the next vertex to be chosen is $v_{i+8}$ where $N[v_{i+4}] \neq N[v_{i+8}]$. Proceeding like this we choose the upper irredundant set as $\{v_1, v_1+4, v_1+8, \ldots, v_1+\left(\left\lceil \frac{n-1}{n} \right\rceil \right)\}$ where the suffices modulo $n$. Hence the proof.

Example 2.8. For the graph $G(11)$ given in the figure 2.4, the upper irredundant sets are $\{v_1, v_5\}$, $\{v_2, v_6\}$, $\{v_3, v_7\}$, $\{v_4, v_8\}$, $\{v_5, v_9\}$, $\{v_6, v_{10}\}$, $\{v_7, v_{11}\}$, $\{v_8, v_1\}$, $\{v_9, v_2\}$, $\{v_{10}, v_3\}$ and $\{v_{11}, v_4\}$.

Theorem 2.9. In $G(n)$, if $n$ is a multiple of 4. Then $G(n)$ contains only 4 upper irredundant sets.

Proof. Let $G(n)$ be a 6-regular graph with girth 3 and $n$ be a multiple of 4. Then $n = 4m$ where $m \geq 2$. Now by Theorem 2.7, the upper irredundant set for $G(4m)$ are $S' = \{v_i, v_i+4, v_i+8, \ldots, v_i+(m-1)4\} = \{v_i, v_i+4, \ldots, v_i+n-4\}$ where $1 \leq i \leq n$, $m \geq 2$ and the suffices modulo $n$.

Now we consider for two cases $m = 2$ and $m > 2$.

Case 1. $m = 2$

Here, $G(n) = G(8)$. Consider the graph $G(8)$ given in figure 2.5. The upper irredundant sets are $\{v_1, v_5\}$, $\{v_2, v_6\}$, $\{v_3, v_7\}$ and $\{v_4, v_8\}$. Thus $G(n)$ contains only 4 upper irredundant sets.

Figure 2.3: $G(21)$

Figure 2.4: $G(11)$

Figure 2.5: $G(8)$
Case 2. $m > 2$

The minimum irredundant set are $S_i = \{v_i, v_{i+4}, \ldots, v_{i+n-4}\}$ where $1 \leq i \leq n$ and the suffixes modulo $n$. Here, $S_1 = \{v_1, v_5, \ldots, v_{n-3}\}$, $S_2 = \{v_2, v_6, \ldots, v_{n-2}\}$, $S_3 = \{v_3, v_7, \ldots, v_{n-1}\}$ and $S_4 = \{v_4, v_8, \ldots, v_n\}$. Proceeding like this we get $S_p = \{v_p, v_{p+4}, \ldots, v_{p+n-4}\}$ where $5 \leq p \leq n$. Since the suffixes are modulo $n$, $S_j$ is either $S'_i$ or $S''_i$ or $S''_i$ or $S_4$ according as $p \equiv 1 \mod 4$ or $p \equiv 2 \mod 4$ or $p \equiv 3 \mod 4$ or $p \equiv 0 \mod 4$, respectively. Thus, $G(n)$ contains only 4 upper irredundant sets.

Example 2.10. Consider the graph $G(16)$ given in figure 2.6. The upper irredundant sets are $\{v_1, v_5, v_9, v_{13}\}$, $\{v_2, v_6, v_{10}, v_{14}\}$, $\{v_3, v_7, v_{11}, v_{15}\}$ and $\{v_4, v_8, v_{12}, v_{16}\}$. Thus, $G(16)$ contains only 4 upper irredundant set.

![Figure 2.6: G(16)](image)

**Theorem 2.11.** For the 6-regular graph with girth 3 and $n$ vertices $G(n)$, $ir(G(n)) = \lceil \frac{n-3}{4} \rceil$, for $n \geq 8$.

**Proof.** By Theorem 2.3, the minimum irredundant sets are $S = \{v_i, v_{i+7}, v_{i+14}, \ldots, v_{i+\lceil \frac{n-3}{4} \rceil}\}$ where $1 \leq i \leq n$ and the suffixes modulo $n$. Hence, $ir(G(n)) = |S| = \lceil \frac{n}{4} \rceil$, for $n \geq 8$.

![Figure 2.7: G(12)](image)

**Theorem 2.13.** For the six regular graph with girth 3 and $n$ vertices $G(n)$, $IR(G(n)) = \lceil \frac{n-3}{4} \rceil$, for $n \geq 8$.

**Proof.** By Theorem 2.7, $S' = \{v_i, v_{i+4}, v_{i+8}, \ldots, v_{i+\lceil \frac{n-3}{4} \rceil}\}$ where $1 \leq i \leq n$ and $i + \left(\lfloor \frac{n-3}{4} \rfloor - 1\right) 4 \mod n$ is an upper irredundant set. Hence, $IR(G(n)) = |S'| = \lceil \frac{n-3}{4} \rceil$, for $n \geq 8$.

Example 2.14. Consider the graph $G(8)$ given in Figure 2.5. There are 4 upper irredundant sets for $G(8)$ which are $\{v_1, v_5\}, \{v_2, v_6\}, \{v_3, v_7\}$ and $\{v_4, v_8\}$. Hence, $IR(G) = \lceil \frac{5-3}{4} \rceil$. This implies that $IR(G) = 2$.

### 3. Relation between $ir(G(n)), IR(G(n))$ and $\gamma(G(n))$

In this section, we establish the relation among irredundant, upper irredundant number and domination number of six regular graph $G(n)$.

**Theorem 3.1.** For the six regular graph $G(n)$ with girth 3, $\gamma(G(n)) = ir(G(n)) + 1$, for $n \geq 8$.

**Proof.** Let $G(n)$ be a six regular graph with girth 3. For $n = 7$, the graph $G(7) = K_7$ is complete and so $\gamma(G) = 1$. But $ir(G) \geq 2$. Thus, in this case $\gamma(G) \neq ir(G)$.

Now let $n \geq 8$. Let $S$ be a minimum dominating set of $G$. To prove $S$ is an irredundant in $G$. Suppose there exists $v$ in $S$ such that $v$ is not irredundant in $S$. Then, $N[v] = N[S - \{v\}]$ implies that $S$ is redundant. Hence by Observation 2.2, $G(n) = K_7$ is complete and hence $n = 7$ which is a contradiction. Therefore, $S$ is an irredundant set in $G$.

Now to prove $S$ has a minimum cardinality of maximal irredundant set in $G$. If $S$ is a minimum dominating set in $G$, then $S$ is a minimal dominating set. Since, every minimal dominating set is a maximal irredundant set[1]. This shows that $S$ is a maximal irredundant set. Since $G$ is a six regular graph of girth 3, $S$ is an irredundant set of minimum cardinality. Hence, $ir(G) = |S| = \gamma(G)$.

![Tree](image)
Example 3.2. Consider the graph $G(22)$ given in figure 2.8. A minimal dominating set of $G(22)$ is $\{v_1, v_8, v_{15}, v_{22}\}$ and hence $\gamma(G) = 4$. A minimal irredundant set of $G(22)$ is $\{v_3, v_{10}, v_{17}, v_2\}$ and hence $ir(G) = 4$. Thus $\gamma(G) = ir(G)$.

By Theorem 2.3, $S = \{v_1, v_8\}$ is a minimum irredundant set and by Theorem 2.7, $S' = \{v_1, v_5, v_9\}$ is an upper irredundant set. This implies that $ir(G(n)) = 2$ and $IR(G(n)) = 3$ and hence $ir(G(n)) < IR(G(n))$.

Case 2. $n \geq 16$

By Theorem 2.3, $S = \{v_1, v_{i7}, v_{i+4}, \ldots, v_{i+\lceil \frac{n}{2} \rceil - 1}\}$ is a minimum irredundant set and by Theorem 2.7, $S' = \{v_{i+4}, v_{i+8}, \ldots, v_{i+\lceil \frac{n}{2} \rceil - 14}\}$ is an upper irredundant set. This implies that $|S| < |S'|$ and hence $ir(G(n)) < IR(G(n))$. □

Example 3.6. Consider the graph $G(21)$ given in figure 2.3. A minimal irredundant set of $G(21)$ is $\{v_1, v_5, v_{15}\}$ and hence $ir(G) = 3$. An upper irredundant set of $G(21)$ is $\{v_1, v_5, v_9, v_{13}, v_{17}\}$ and hence $IR(G) = 5$. This implies that $ir(G(n)) < IR(G(n))$.

Theorem 3.7. If $G(n)$ is a six regular graph with girth 3, then $\gamma(G) \leq IR(G)$ for $n \geq 8$.

Proof. Let $S$ be a minimum dominating set of $G(n)$. Then for every vertex $v$ in $V - S$ which are adjacent to at least one vertex in $S$. Since $S$ is a minimal dominating set, it is an irredundant set. Also, since $G(n)$ is a six regular graph with girth 3, by Theorem 3.1, $\gamma(G) = ir(G)$. Therefore, $ir(G) = |S|$. Also by Theorem 3.3 and by Theorem 3.7, $ir(G) \leq IR(G)$ implies that the cardinality of an irredundant set is always less than or equal to the cardinality of the upper irredundant set. So, we conclude that the domination number is less than or equal to the upper irredundant number. Hence, $\gamma(G) \leq IR(G)$, $n \geq 8$. □

Example 3.8. Consider the graph $G(23)$ given in figure 2.9. A minimal domination set of $G(23)$ is $\{v_1, v_8, v_{15}, v_{22}\}$ and hence $\gamma(G) = 4$. An upper irredundant set of $G(23)$ is $\{v_1, v_5, v_9, v_{13}, v_{17}, v_{21}\}$ and hence $IR(G) = 5$. This implies that $\gamma(G(n)) \leq IR(G(n))$.

Theorem 3.5. For the graph $G(n)$, $ir(G(n)) < IR(G(n))$, for $n = 12, 13, 14$ and $n \geq 16$.

Proof. Let $v_1, v_2, \ldots, v_n$ be the vertices of six regular graph with girth 3 such that $v_1v_2 \ldots v_nv_1$ form a cycle. We consider the following cases.

Case 1. $n = 12, 13, 14$
4. Conclusion

In this paper we have discussed the exact values for $ir(G(n))$ and $IR(G(n))$. Also we have proved $\gamma(G(n)) = ir(G(n)), n \geq 8$; $ir(G(n)) = IR(G(n))$ for $n = 8, 9, 10, 11$ and $15$; $\gamma(G) \leq IR(G(n))$ for $n \geq 8$.

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ISSN(P):2319 – 3786
Malaya Journal of Matematik
ISSN(O):2321 – 5666
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