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Graph Equations Connecting Glue Graphs, Complement Glue Graphs, Line Graphs and Eccentric Graphs

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Abstract: *For any graph G, the Equi-eccentric point set graph G_{ee} is a graph with vertex set V(G) and two vertices are adjacent if and only if they correspond to two vertices of G with equal eccentricities. The Glue graph G_g of G is a graph with the same vertex set V(G) and two vertices are adjacent if and only if they correspond to two adjacent vertices of G_{ee} or two adjacent vertices of G. In this paper, we solve graph equations involving Glue graphs, Complement Glue graphs, Line graphs and Eccentric graphs.*

Key words: *Equi-eccentric point set graph, Glue graph, Complement Glue graph, eccentric graph.*

1. Introduction

Graphs discussed in this paper are simple, undirected and finite. Throughout this paper G means a connected (p, q) graph with radius r and diameter d.

Let V(G) and E(G) denote the vertex set and edge set of graph G respectively. Eccentricity of a vertex u in V(G) is defined by $e_G(u) = \max \{d_G(u, v): v \in V(G)\}$, where $d_G(u, v)$ is the distance between u and v in G. The minimum and maximum of the eccentricities of the graph G are denoted by r(G), the radius of G and d(G), the diameter of G respectively. A graph G is said to be self-centered if d(G) = r(G).

For any graph G, we define the Equi-eccentric point set graph G_{ee} on the same set of vertices by joining two vertices in G_{ee} if and only if they correspond to two vertices of G with equal eccentricities. Also, we define the Glue graph G_g on the same set of vertices by joining two vertices in G_g if and only if they correspond to two adjacent vertices of G or two adjacent vertices of G_{ee}, that is $E(G_g) = E(G) \cup E(G_{ee})$. We define the Complement Glue graph G_{cg} on the same set of vertices by joining two vertices in G_{cg} if and only if they correspond to two adjacent vertices of $\overline{G}$ or two adjacent vertices of G_{ee}, that is $E(G_{cg}) = E(\overline{G}) \cup E(G_{ee})$.

The importance of perfect graphs is both theoretical and practical because of their application to perfect channels in communication theory, problems in operations research,

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optimizing municipal services etc. The Glue graph G_g and the Complement Glue graph G_{cg} are Hamiltonian and perfect. Also, G is a spanning sub graph of G_g and $\overline{G}$ is a spanning sub graph of G_{cg} and connectivity of G_g increases and diameter of G_g decreases as that of G. Hence, these graphs will be useful in communication theory.

Let $E_k = \{ u \in V(G): e_G(u) = k\}$. $|E_k| = c_k$. We have $c_r \geq 1$, $c_{r+i} \geq 2$, i =1, 2, …, d-r. [2]

For any graph G, the eccentric graph G_e has the same set of vertices and any two vertices of G_e are adjacent if and only if one of the two vertices has maximum possible distance from the other, that is $V(G_e)= V(G)$ and $uv \in E(G_e)$ if any only if $d_G(u, v) = \min\{e(u), e(v)\}$ [2]. The super eccentric graph J(G) has the same vertex set as that of G and any two vertices u and v are adjacent in J(G) if and only if $d_G(u, v) \geq r$, where r is the radius of the graph G [6]. The definitions and details not furnished here may be found in [4] and [5]. We need the following results.

Result 1.1 [3] :

G_g is two connected.

Result 1.2 [3] :

Vertices of G_g can be partitioned into $E_r, E_{r+1}\ldots E_d$ such that $V(G_g) = E_r \cup \ldots \cup E_d$ and each $< E_{r+i} >$ is complete in G_g, i = 0,1,…, d−r.

Result 1.3 [5] :

G is a line graph if and only if the lines (edges) of G can be partitioned into complete sub graphs in such a way that no vertex lies in more than two of those subgraphs.

2. Graph equations involving G, G_g, G_e and J(G)

I. $G = G_g$

$G = G_g$ implies that all the edges in G_{ee} are in G also. Therefore, G is complete. Thus, we have the following theorem.

Theorem 2.1 :

$G = G_g$ if and only if G is complete.

II. $G_e = G_g$

G_e is the eccentric graph of G. For u, v $\in$ V(G), uv $\in$ E(G_e) if and only if $d_G(u, v) = \min(e(u), e(v))$ in G. Hence $G_g = G_e$ implies minimum eccentricity must be one in G, since G_g contains edges of G also. This implies that G is a graph with radius one and G has no edge joining vertices of eccentricity two. (Since if G contains an edge x joining vertices of eccentricity two, G_e cannot have the edge x) Thus, we have the following theorem.

Theorem 2.2 :

$G_e = G_g$ if and only if $G = K_n$ or G is a connected graph with radius one and diameter two such that $V(G) = E_1 \cup E_2$ where $< E_1 >$ is complete and $< E_2 >$ is totally disconnected.

III. $J(G) = G_g$

J(G) is the super eccentric graph of G and the edge uv $\in$ E(J(G)) if and only if $d_G(u, v) \geq r$. Hence, $J(G) = G_g$ if and only if radius (G) = 1, thus we have,

Theorem 2.3 :

$J(G) = G_g$ if and only if radius (G) = 1.

Note that in the previous two theorems $G_g = K_n$.

3. Graph equations involving L(G) and G_g

First let us solve the graph equation $L(G) = G_g$.

IV. $L(G) = G_g$:

If $L(G) = G_g$, the number of vertices of G is equal to the number of edges of G, that is G is uni-cyclic. Also, we know that G_g is two connected and G_g is complete or the vertices of G_g can be partitioned in such a way that, they form complete sub graphs [7]. Hence, the only solution is $G = K_3$. Thus we have proved,

Theorem 3.1 :

$L(G) = G_g$ if and only if $G = K_3$.

Now, consider the graph equation $L(H) = G_g$, $H \neq G$. To solve this graph equation we need the following lemma.

Lemma 3.1 :

Let G be a connected graph with radius r and diameter d. Then for G_g is a line graph, $d-r+1 < 2$ if $< E_r \cup E_{r+1} >$ is not complete in G_g and $d-r+1 < 3$ if $< E_r \cup E_{r+1} >$ is complete in G_g.

Proof: Assume G_g is a line graph.

Case 1: $< E_r \cup E_{r+1} >$ is not complete in G_g.

In G_g, $< E_r >, < E_{r+1} >, \ldots, < E_d >$ are complete sub graphs. Since G_g is a line graph, any vertex in E_{r+1} is adjacent to at most one vertex in E_r, otherwise it will lead to a contradiction to result 1.3. Also any point $v_{r+1} \in E_{r+1}$ is adjacent to at most one vertex in E_{r+2} and so on. In this situation there must exist at least one $v_{r+1} \in E_{r+1}$ having adjacent vertices in E_r and E_{r+2}. Therefore, this v_{r+1} lies on at least three complete sub graphs if $< E_r \cup E_{r+1} >$ is not complete. Hence $d-r+1$ must be at most 2 if $< E_r \cup E_{r+1} >$ is not complete is G_g.

Case 2: $< E_r \cup E_{r+1} >$ is complete is G_g .

As in the previous case we can prove $d-r+1 < 3$. This proves the lemma.

V. $L(H) = G_g$:

Case 1: G is a self-centered graph with n vertices.

In this case, $G_g = K_n$. Take $H = K_{1,n}$, then $L(H) = K_n$. Therefore, $(G, H) = (F, K_{1,n})$ is the solution of $L(H) = G_g$, where F is any self-centered graph with n vertices.

Case 2: G is a bi-eccentric graph with diameter two.

In this case also, $G_g = K_n$. Hence, as is the previous case $(F, K_{1,n})$ is the solution of $L(H) = G_g$.

Case 3: G is not self-centered and $r(G) \neq 1$.

$L(H) = G_g$ implies G_g is a line graph. Hence by lemma 3.1, $d-r+1 \leq 2$, if $< E_r \cup E_{r+1} >$ is not complete is G_g, and $d-r+1 \leq 3$ if $< E_r \cup E_{r+1} >$ is complete. Therefore, $d-r+1 = 2$ or 3, since G is not self-centered and $r(G) \neq 1$.

Sub case 3.1: $< E_r \cup E_{r+1} >$ is not complete in G_g.

First, let us assume G contains more than one central vertex v_r. Let $v_r \in E_r$ be adjacent to k ($<c_{r+1}$) vertices of E_{r+1} in G. $< E_r \cup E_{r+1} >$ is not complete. Hence, $d-r+1$ is at most 2 by lemma 3.1. Also vertices with eccentricity r are adjacent to at most one vertex with eccentricity r+1 in G. Thus, G is a bi-eccentric graph such that each vertex in this is adjacent to at most one vertex in E_{r+1}. $|E_r| = c_r$, $|E_{r+1}| = c_{r+1}$.

Consider H (as in Figure 3.1) with $\deg v_1 = c_r$, $\deg v_2 = c_{r+1}$.

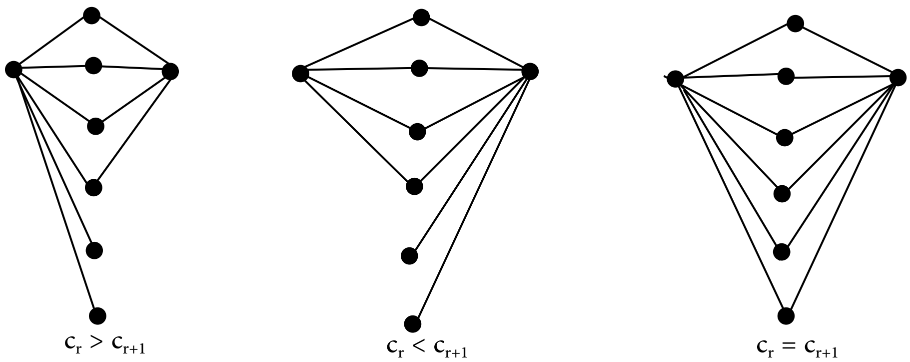


Figure 3.1

This H satisfies the equation $L(H) = G_g$. If $c_r = c_{r+1}$. H is the generalized θ-graph.

Now, assume G contains only one central vertex v_r. v_r is adjacent to k vertices of E_{r+1}, where $2 \leq k < c_{r+1}$. Clearly, deg v_r = k in G, and if k > 2, G_g is not a line graph, since v_r is in more than two complete graphs formed by the edges of G_g. Therefore, k must be two and hence G is bi-eccentric with only one central node adjacent to exactly two nodes of eccentricity r+1. Hence, H is of the form $K_{1,\,n-1}+x$, where $n = |V(G)|$.

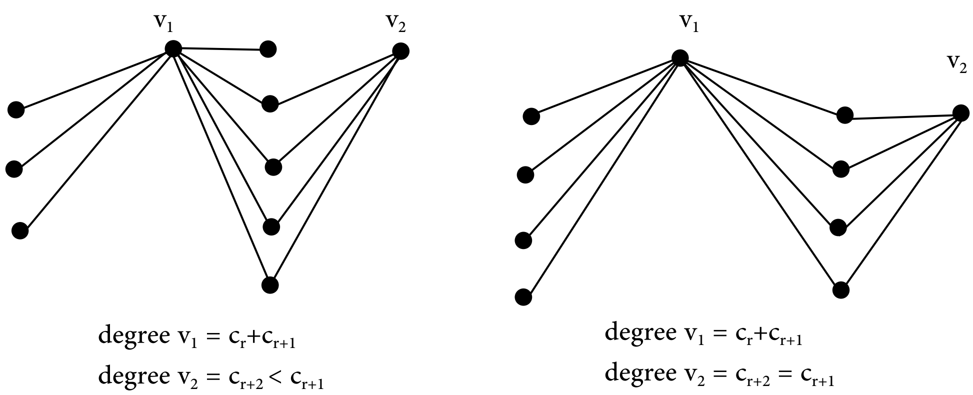
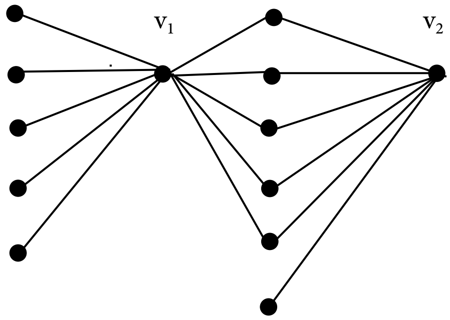


Figure 3.2 (a)

Sub case 3.2 $< E_r \cup E_{r+1} >$ is complete in G_g.

In this case, G has one or more central vertices such that each $v_r \in E_r$ is adjacent to all the vertices of E_{r+1} and $d-r+1 = 3$ by lemma 3.1. Also, each vertex in E_{r+1} is adjacent to at most one vertex of E_{r+2} and vice-versa. $|E_r| = c_r$, $|E_{r+1}| = c_{r+1}$, $|E_{r+2}| = c_{r+2}$. Then H as in Figure 3.2, satisfies $L(H) = G_g$.



degree $v_1 = c_r + c_{r+1}$
degree $v_2 = c_{r+2} > c_{r+1}$

Figure 3.2(b)

Thus we have,

Theorem 3.2

$L(H) = G_g$ if and only if (G, H) satisfies any one of the following :

(1) $(F, K_{1,n})$, where F is self-centered with n vertices or bi-eccentric with diameter two.

(2) (F_1, F_1'), where F_1 is bi-eccentric such that each vertex in E_r is adjacent to at most one vertex in E_{r+1} and F_1' is any one of the graphs in fig:3.1.

(3) (F_2, F_2'), where F_2 is a tri-eccentric graph such that each $v_r \in E_r$ is adjacent to all vertices of E_{r+1} and an element in E_{r+1} is adjacent to at most one element in E_{r+2} and vice versa. F_2 is any one of the graphs in Figure 3.2.

(4) (F_3, F_3'), where F_3 is bi-eccentric with unique central vertex adjacent to exactly two vertices of eccentricity r+1, $F_3' = K_{1,n-1}+x$.

Now, we shall solve the graph equation $L(H) = \overline{G_g}$

VI. $L(H) = \overline{G_g}$:

Case 1 : G is a graph with more than three central vertices ; $c_r \geq 3$.

Since $c_r \geq 3$, in G_g, there is a K_3 containing vertices of E_r, say v_r, v_r', and v_r''. Suppose $d-r+2 \geq 3$; there exists a $v_{r+2} \in E_{r+2}$ such that the vertices v_r, v_r', v_r'' and v_{r+2} form a $K_{1,3}$ (induced) in $\overline{G_g}$. Therefore, $\overline{G_g}$ is not a line graph. Hence, $d-r+1$ must be at most 2 if $\overline{G_g}$ is a line graph, that is G is self-centered or bi-eccentric.

Sub case 1.1: G is self-centered.

Since G is self-centered, G_g is complete. Hence, if $n = |V(G)|$, $\overline{G_g} = nK_1$. Therefore, $H = nK_2$ satisfies the relation $L(H) = \overline{G_g}$.

Sub case 1.2: G is bi-eccentric with radius r.

Suppose each vertex in E_r is adjacent to all the vertices of E_{r+1}, $G_g = K_n$. Hence, again $H = nK_2$ satisfies the relation $L(H) = \overline{G_g}$.

Suppose there exists vertices in E_r, which are not adjacent to all the elements of E_{r+1}. Suppose $v_r \in E_r$ is not adjacent to more than two elements in E_{r+1}. Then G_g contains $\overline{K_{1,3}}$, and hence $\overline{G_g}$ cannot be a line graph. Hence, $v_r \in E_r$ must be adjacent to at least $c_{r+1}-2$ elements in E_{r+1}, for all $v_r \in E_r$. Hence in $\overline{G_g}$, $v_r \in E_r$ is adjacent to at most two elements in E_{r+1}, that is deg v_r in $\overline{G_g}$ is ≤ 2. Similarly, we can prove deg v_{r+1} in $\overline{G_g}$ is ≤ 2 for all $v_{r+1} \in E_{r+1}$. Hence, if $\overline{G_g}$ is a line graph, $\overline{G_g}$ is a path or cycle or $\overline{G_g}$ is disconnected whose components are paths or cycles or isolated vertices. Let $G_g = mK_1 \cup P_r \cup P_s \ldots \cup C_x \cup C_y \ldots \cup C_z$, then $H = mK_2 \cup P_{r+1} \cup P_{s+1} \cup \ldots \cup C_{x+1} \cup \ldots \cup C_{z+1}$ such that $L(H) = \overline{G_g}$.

Case 2: G has at most two central vertices.

Sub case 2.1: Each element in Er is adjacent to all the elements of E_{r+1}.

In this case, G_g is a line graph only when $d-r+1 \leq 3$ (otherwise if $v \in E_{r+3}$, v, v_r, v_{r+1}, v_{r+1}' form a $\overline{K_{1,3}}$ in G_g. $v_r \in E_r$, $v_{r+1}, v_{r+1}' \in E_{r+1}$). When $d-r+1 = 1$ or 2 that is when G is self-centered or bi-eccentric, G_g is complete and $\overline{G_g} = nK_1$ and $H = nK_2$ satisfies $L(H) = \overline{G_g}$ when $d-r+1 = 3$, we claim that $|E_{r+1}| = c_{r+1} = 2$ and $|E_{r+2}| = c_{r+2}$.

Suppose $c_{r+2} > 2$, $v_r \in E_r$ and any three elements in E_{r+2} form a $\overline{K_{1,3}}$ in G_g. Hence, c_{r+2} must be two. Also, we know any element in E_{r+1} cannot be adjacent to all the elements of E_{r+2}. Therefore, each element in E_{r+1} is adjacent to at most one element in E_{r+2}. Hence if $c_{r+1} > 2$, there exists a $\overline{K_{1,3}}$ in G_g formed by $v_r \in E_r$, $v_{r+1}, v_{r+1}' \in E_{r+1}$, and $v_{r+2} \in E_{r+2}$, where v_{r+1}, v_{r+1}' are not adjacent to v_{r+2} in G. Hence, c_{r+1} must be two. Therefore, G_g must be any one of F_1, F_2 (Fig: 3.3). But again F_1 has a $\overline{K_{1,3}}$. Therefore, $G_g = F_2$, that is $G = P_5$, $\overline{G_g} = P_5$.

Hence, $H = P_6$ satisfies $\overline{G_g} = L(H)$.

F_2 F_1

Figure 3.3

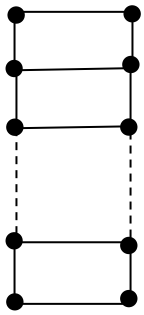


Figure 3.4

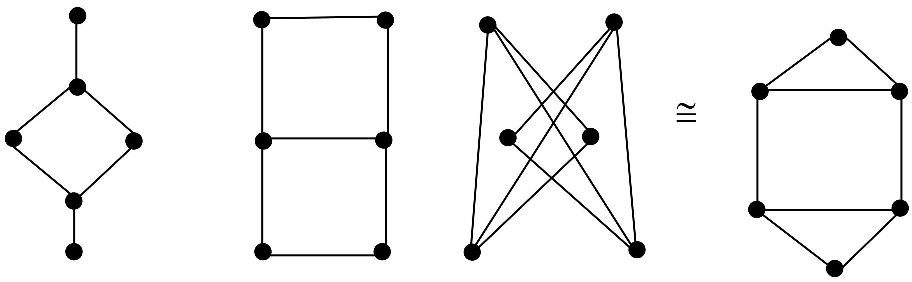
Sub case 2.2: Each element in E_r is not adjacent to all the elements of E_{r+1}

(a) Suppose $c_r = 2$: E_r, $E_{r+1}\ldots$ contains exactly two elements if $d-r+2 > 2$ (otherwise $\overline{K_{1,3}}$ in G_g) and there cannot be any triangles, since any element of E_i cannot be adjacent to every element of E_{i+1} and vice versa $(i > r)$. Therefore, G_g is as in Figure 3.4. If $d-r+1 > 3$, G_g contains $K_2 \cup K_{1,2}$ and hence $\overline{G_g}$ contains the forbidden sub graph G_2 as induced sub graph. Hence, $d-r+1 \leq 3$, When $d-r+1=3$, H = F (Figure 3.5) satisfies $L(H) = \overline{G_g}$

When $d-r+1 = 2$, G is bi-eccentric with two central vertices each is not adjacent to at most $c_{r+1}-1$ elements of E_{r+1}, If E_r contains an element, which is not adjacent to more than three elements in E_{r+1}, $\overline{K_{1,3}}$ is an induced sub graph of G_g. Hence, each element in E_r is not adjacent to at most two elements in E_{r+1} and vice versa.

This gives degree of every vertex is one or two in $\overline{G_g}$. Thus, $\overline{G_g}$ has paths or cycles as components. Therefore, H is a path or cycle or a disconnected graph having components as paths or cycles such that $L(H) = \overline{G_g}$.

When $d-r+1 = 1$, G is self-centered, $G_g = K_2$, $H = 2K_2$ such that $L(H) = \overline{G_g}$.



H = F $\qquad$ G_g $\qquad$ $\overline{G_g}$

Figure 3.5

(b) Suppose c_r = 1. Then d−r+1 is at most 3 as in the previous case.

When d−r+1 = 3, E_{r+2} must contain exactly two elements. Otherwise, $\overline{K_{1,3}}$ is present in $\overline{G_g}$. Let $E_r = \{v_r\}$, then v_r must be adjacent to at least two elements of E_{r+1} and v_r must be adjacent to $c_{r+1}-2$ or $c_{r+1}-1$ elements of E_{r+1} (otherwise, there exists induced $\overline{K_{1,3}}$ in G_g). Also every element of E_{r+2} must be adjacent to at least $c_{r+1}-2$ elements in E_{r+1} (otherwise, $\overline{K_{1,3}}$ is in G_g). But there exists no vertex in E_{r+1}, which is adjacent to both the elements of E_{r+2}. Hence, c_{r+1} = 3 or 4. But these cases are not possible under the given conditions.

When d−r+1 = 2, v_r is not adjacent to at most two elements of E_{r+1}. Hence, in $\overline{G_g}$, deg v_r = 1 or 2. Therefore, $\overline{G_g} = K_2 \cup (n-2) K_1$ or $\overline{G_g} = K_{1,2} \cup (n-3) K_1$, where n = |V(G)|. Hence, $H = K_{1,2} \cup (n-2)K_2$ or $P_4 \cup (n-3)K_2$ satisfies the equation $L(H) = \overline{G_g}$.

When d−r+1 = 1, G = K_1, H = K_2.

Thus, we have the following theorem.

Theorem 3.3

For any two graphs G and H, the equation $\overline{G_g}$ = L(H) holds if (G, H) equals to one of the pairs of graphs given in the following.

(1) (G, H), where G is bi-eccentric such that each central vertex is not adjacent to at most two peripheral vertices. H is the union of paths, cycles and isolated vertices.

(2) (G, H), G is self-centered or bi-eccentric with radius one and H = nK_2, when n = |V(G)|.

(3) (G, H), G = P_5, H = P_6.

(4) (G, H), G = P_6, H = F in Figure 3.5

Remark: In [1] Jin Akiyama et al have solved graph equations involving line graphs, middle graphs and total graphs. Using this and Theorems 3.2 and 3.3 we can solve the graph equations M(H) = G_g, $\overline{M}(H) = G_g$, T(H) = G_g and $\overline{T}(H) = G_g$.

4. Graph equations involving G_{cg}

VII. G_{cg} = L(H)

In G_{cg}, < E_r >, <E_{r+1}>, ..., <E_d> are complete sub graphs. Hence, G_{cg} is a line graph implies any vertex in E_{r+i} is adjacent to at most one element of E_{r+i+1} or E_{r+i-1} in G_{cg}. This gives each element in E_k, k > r is adjacent to all elements of E_{k-1} or E_{k+1} in G. This is possible only when n = d−r+1 ≤ 3.

Case 1: n = 3.

Elements in E_{r+1} cannot be adjacent to all the elements of E_{r+2} in G. Hence, each element in E_{r+1} is adjacent to every element of E_r in G and each element of E_{r+2} is not adjacent to at most one element of E_{r+1} and vice-versa. This is possible only when $c_{r+1} = c_{r+2} = 2$. Thus, G is a graph with radius two diameter four and $c_{r+1} = c_{r+2} = 2$ such that each vertex of E_{r+1} is adjacent to every vertex of E_r and vice-versa. Here H is as in Figure 4.1

Case 2: n = 2.

Subcase 2.1: r(G) = 1 and d(G) = 2

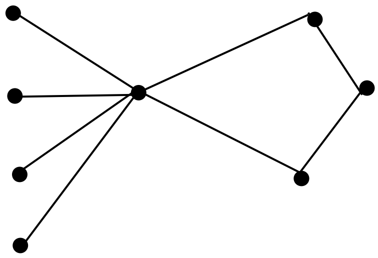


Figure 4.1

In this case, each element of E_r is adjacent to every elements of E_{r+1} in G. Hence, G_{cg} is disconnected and has two components which are complete, that is $G_{cg} = K_m \cup K_n$, where $m = c_r$ and $n = c_{r+1}$. $H = K_{1,m} \cup K_{1,n}$ satisfies $L(H) = G_{cg}$.

Subcase 2.2: r(G) > 1.

In G_{cg}, $< E_r >$, $< E_{r+1} >$ are complete and hence, G_{cg} is a line graph if and only if each element of E_r is adjacent to at most one element of E_{r+1} and vice-versa in G_{cg}. Hence in G, each element of E_r is adjacent to c_{r+1}-1 elements of E_{r+1} and each element of E_{r+1} is adjacent to $c_r - 1$ elements of E_r. This is possible only when $c_r = c_{r+2} = 2$. Since r(G) > 1 and G is not self-centered, $G = P_4$. $H = G_{cg} = C_4$.

Case 3 : n = 1.

In this case, G is self-centered and G_{cg} is complete and hence it is a line graph. $H = K_{1,p}$ satisfies the graph equation $G_{cg} = L(H)$.

Hence, we have the following theorem:

Theorem 4.1

For any two graphs G and H the equation $G_{cg} = L(H)$ holds if and only if (G, H) equals to one of the pairs of graphs given in the following:

(1) $(G, K_{1,p})$, where G is self-centered.

(2) $(G, K_{1,m} \cup K_{1,p-m})$, where G is a bi-eccentric graph with radius one, having m central vertices.

(3) (P_4, C_4).

VIII. $\overline{G}_{cg}$ = L(H)

$\overline{G}_{cg}$ has no triangles. Hence, maximum number of vertices in a complete subgraph of $\overline{G}_{cg}$ is two. Hence, $\overline{G}_{cg}$ is a line graph if no vertex of $\overline{G}_{cg}$ lies in more than two edges; that is degree of vertices in $\overline{G}_{cg}$ is at most two. Therefore, $\overline{G}_{cg}$ is union of paths and cycles. In this case, H is union of paths and cycles also. Hence, $\overline{G}_{cg}$ is a line graph if and only if G is a graph in which each vertex v in V(G) has at most two adjacent vertices with eccentricity not equal to e(v). Thus, we have the following theorem.

Theorem 4.2

For any two graphs G and H the equation $\overline{G}_{cg}$ = L(H) holds if and only if G is a graph in which each vertex v in V(G) has at most two adjacent vertices with eccentricity not equal to e(v) and H is the union of paths and cycles satisfying $\overline{G}_{cg}$ = L(H).

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