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SIGNED GRAPH EQUATIONS: $N(\Sigma) \sim CMD(\Sigma)$; $CMD(\Sigma) \sim MD(\Sigma)$; $MD(\Sigma) \sim L(\overline{\Sigma})$

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ABSTRACT. In this paper, we obtained the following switching equivalence characterizations: $N(\Sigma) \sim CMD(\Sigma)$, $CMD(\Sigma) \sim MD(\Sigma)$ and $MD(\Sigma) \sim L(\overline{\Sigma})$, where $N(\Sigma)$, $CMD(\Sigma)$, $MD(\Sigma)$ and $L(\overline{\Sigma})$ are neighborhood signed graph, common minimal signed graph, minimal dominating signed graph and line signed graph of complementary signed graph of Σ respectively.

1. Introduction

For standard terminology and notation in graph theory we refer Harary [**8**] and Zaslavsky [**48**] for signed graphs. Throughout the text, we consider finite, undirected graph with no loops or multiple edges.

Within the rapid growth of the Internet and the Web, and in the ease with which global communication now takes place, connectedness took an important place in modern society. Global phenomena, involving social networks, incencitives and the behavior of people based on the links that connect us appear in a regular manner. Motivated by these developements, there is a growing multidisciplinary interest to understand how highly connected systems operate [**6**].

In social sciences we often deal with relations of opposite content, e.g., "love"-"hatred", "likes"-"dislikes", "tells truth to"-"lies to" etc. In common use opposite relations are termed positive and negative relations. A signed graph is one in which relations between entities may be of various types in contrast to an unsigned graph

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where all relations are of the same type. In signed graphs edge-coloring provides an elegant and uniform representation of the various types of relations where every type of relation is represented by a distinct color.

In the case where precisely one relation and its opposite are under consideration, then instead of two colors, the signs + and - are assigned to the edges of the corresponding graph in order to distinguish a relation from its opposite. In the case where precisely one relation and its opposite are under consideration, then instead of two colors, the signs + and − are assigned to the edges of the corresponding graph in order to distinguish a relation from its opposite. Formally, a signed graph $\Sigma = (\Gamma, \sigma) = (V, E, \sigma)$ is a graph Γ together with a function that assigns a sign $\sigma(e) \in \{+, -\}$, to each edge in Γ. σ is called the signature or sign function. In such a signed graph, a subset A of $E(\Gamma)$ is said to be positive if it contains an even number of negative edges, otherwise is said to be negative. Balance or imbalance is the fundamental property of a signed graph. A signed graph Σ is balanced if each cycle of Σ is positive. Otherwise it is unbalanced.

Signed graphs Σ_1 and Σ_2 are isomorphic, written $\Sigma_1 \cong \Sigma_2$, if there is an isomorphism between their underlying graphs that preserves the signs of edges.

The theory of balance goes back to Heider [**11**] who asserted that a social system is balanced if there is no tension and that unbalanced social structures exhibit a tension resulting in a tendency to change in the direction of balance. Since this first work of Heider, the notion of balance has been extensively studied by many mathematicians and psychologists. In 1956, Cartwright and Harary [**4**] provided a mathematical model for balance through graphs.

A *marking* of Σ is a function $\zeta : V(\Gamma) \to \{+, -\}$. Given a signed graph Σ one can easily define a marking ζ of Σ as follows: For any vertex $v \in V(\Sigma)$,

$$\zeta(v) = \prod_{uv \in E(\Sigma)} \sigma(uv),$$

the marking ζ of Σ is called *canonical marking* of Σ.

The following are the fundamental results about balance, the second being a more advanced form of the first. Note that in a bipartition of a set, $V = V_1 \cup V_2$, the disjoint subsets may be empty.

Proposition 1.1. *A signed graph Σ is balanced if and only if either of the following equivalent conditions is satisfied:*

- **(i):** *Its vertex set has a bipartition $V = V_1 \cup V_2$ such that every positive edge joins vertices in V_1 or in V_2, and every negative edge joins a vertex in V_1 and a vertex in V_2* (Harary [**9**]).
- **(ii):** *There exists a marking μ of its vertices such that each edge uv in Γ satisfies $\sigma(uv) = \zeta(u)\zeta(v)$.* (Sampathkumar [**18**]).

Let $\Sigma = (\Gamma, \sigma)$ be a signed graph. *Complement* of Σ is a signed graph $\overline{\Sigma} = (\overline{\Gamma}, \sigma')$, where for any edge $e = uv \in \overline{\Gamma}$, $\sigma'(uv) = \zeta(u)\zeta(v)$. Clearly, $\overline{\Sigma}$ as defined here is a balanced signed graph due to Proposition 1.1. For more new notions on signed graphs refer the papers (see [**15**–**20**, **22**–**43**, **45**]).

A switching function for Σ is a function $\zeta : V \to \{+, -\}$. The switched signature is $\sigma^{\zeta}(e) := \zeta(v)\sigma(e)\zeta(w)$, where e has end points v, w. The switched signed graph is $\Sigma^{\zeta} := (\Sigma|\sigma^{\zeta})$. We say that Σ switched by ζ. Note that $\Sigma^{\zeta} = \Sigma^{-\zeta}$ (see [**1**]).

If $X \subseteq V$, switching Σ by X (or simply switching X) means reversing the sign of every edge in the cutset $E(X, X^c)$. The switched signed graph is Σ^X. This is the same as Σ^{ζ} where $\zeta(v) := -$ if and only if $v \in X$. Switching by ζ or X is the same operation with different notation. Note that $\Sigma^X = \Sigma^{X^c}$.

Signed graphs Σ_1 and Σ_2 are switching equivalent, written $\Sigma_1 \sim \Sigma_2$ if they have the same underlying graph and there exists a switching function ζ such that $\Sigma_1^{\zeta} \cong \Sigma_2$. The equivalence class of Σ,

$$[\Sigma] := \{\Sigma' : \Sigma' \sim \Sigma\},$$

is called the its switching class.

Similarly, Σ_1 and Σ_2 are switching isomorphic, written $\Sigma_1 \cong \Sigma_2$, if Σ_1 is isomorphic to a switching of Σ_2. The equivalence class of Σ is called its switching isomorphism class.

Two signed graphs $\Sigma_1 = (\Gamma_1, \sigma_1)$ and $\Sigma_2 = (\Gamma_2, \sigma_2)$ are said to be *weakly isomorphic* (see [**44**]) or *cycle isomorphic* (see [**47**]) if there exists an isomorphism $\phi : \Gamma_1 \to \Gamma_2$ such that the sign of every cycle Z in Σ_1 equals to the sign of $\phi(Z)$ in Σ_2. The following result is well known (see [**47**]):

Proposition 1.2. (Zaslavsky [**47**]) *Two signed graphs Σ_1 and Σ_2 with the same underlying graph are switching equivalent if and only if they are cycle isomorphic.*

In [**22**], the authors introduced the switching and cycle isomorphism for signed digraphs.

2. Switching Equivalence of $N(\Sigma)$ and $CMD(\Sigma)$

Motivated by the existing definition of complement of a signed graph, Rangarajan et al. [**17**] extended the notion of neighborhood graphs (see [**5**]) to signed graphs as follows: The *neighborhood signed graph* $N(\Sigma)$ of a signed graph $\Sigma = (\Gamma, \sigma)$ is a signed graph whose underlying graph is $N(\Gamma)$ and sign of any edge uv is $N(\Sigma)$ is $\zeta(u)\zeta(v)$, where ζ is the canonical marking of Σ. Further, a signed graph $\Sigma = (\Gamma, \sigma)$ is called neighborhood signed graph, if $\Sigma \cong N(\Sigma')$ for some signed graph Σ'.

The following result indicates the limitations of the notion $N(\Sigma)$ introduced above, since the entire class of unbalanced signed graphs is forbidden to be neighborhood signed graphs.

Proposition 2.1. (Rangarajan et al. [**17**]) *For any signed graph $\Sigma = (\Gamma, \sigma)$, its neighborhood signed graph $N(\Sigma)$ is balanced.*

Kulli and Janakiram [**14**] introduced a new class of intersection graphs in the field of domination theory. The common minimal dominating graph $CMD(\Gamma)$ of a graph Γ is the graph having same vertex set as G with two vertices adjacent in $CMD(\Gamma)$ if, and only if, there exists a minimal dominating set in Γ containing them.

In [**37**], the authors introduced a natural extension of the notion of common minimal dominating graph to the realm of signed graphs since this appears to have interesting connections with complementary signed graph and neighborhood signed graph.

The *common minimal dominating signed graph* $CMD(\Sigma)$ of a signed graph $\Sigma = (\Gamma, \sigma)$ is a signed graph whose underlying graph is $CMD(\Gamma)$ and sign of any edge uv in $CMD(\Sigma)$ is $\zeta(u)\zeta(v)$, where ζ is the canonical marking of Σ. Further, a signed graph $\Sigma = (\Gamma, \sigma)$ is called common minimal dominating signed graph, if $\Sigma \cong CMD(\Sigma')$ for some signed graph Σ'. The following result restricts the class of common minimal dominating graphs.

Proposition 2.2. (Siva Kota Reddy and Prashanth, [**37**]) *For any signed graph $\Sigma = (\Gamma, \sigma)$, its common minimal dominating signed graph $CMD(\Sigma)$ is balanced.*

In this section, we offer a solution of the following signed graph equation:

$$N(\Sigma) \sim CMD(\Sigma) \qquad (1)$$

In case of graph equation: $N(\Gamma) \cong CMD(\Gamma)$, Swaminathan and Baskar [**46**] obtained the solutions.

Proposition 2.3. (Swaminathan and Baskar, [**46**]) $N(\Gamma) \cong CMD(\Gamma)$ *if, and only if, Γ has the following properties:*

(1) *$diam(\Gamma) \leqslant 2$, and*
(2) *an edge e lies on a triangle if, and only if, there exists a minimal dominating set containing the edge e.*

Here, we solve the signed graph switching equivalence relation (1) in the sense that we determine the structure of all signed graphs satisfying (1).

Proposition 2.4. *For any signed graph $\Sigma = (\Gamma, \sigma)$, $N(\Sigma) \sim CMD(\Sigma)$ if, and only if, Γ satisfies the conditions of Proposition 2.3.*

Proof. Suppose $N(\Sigma) \sim CMD(\Sigma)$. This implies, $N(\Gamma) \cong CMD(\Gamma)$ and hence by Proposition 2.3, we see that the graph Γ must satisfies all the conditions of Proposition 2.3.

Conversely, suppose that Γ satisfies the all the conditions of Proposition 2.3. Then $N(\Gamma) \cong CMD(\Gamma)$. Now, if Σ is a signed graph with underlying graph diam$(\Gamma) \leqslant 2$, and an edge e lies on a triangle if, and only if, there exists a minimal dominating set containing the edge e, by Propositions 2.1 and 2.2, $N(\Sigma)$ and $CMD(\Sigma)$ are balanced and hence, the result follows from Proposition 1.2. □

3. Switching Equivalence of $CMD(\Sigma)$ and $MD(\Sigma)$

Kulli and Janakiram [**13**] introduced a new class of intersection graphs in the field of domination theory. The *minimal dominating graph* $MD(\Gamma)$ of a graph Γ is the intersection graph defined on the family of all minimal dominating sets of vertices in Γ.

In [**43**], the authors extended the notion of $MD(\Gamma)$ to the realm of signed graphs. The *minimal dominating signed graph* $MD(\Sigma)$ of a signed graph $\Sigma = (\Gamma, \sigma)$ is a signed graph whose underlying graph is $MD(\Gamma)$ and sign of any edge PQ in $MD(\Sigma)$ is $\zeta(P)\zeta(Q)$, where ζ is the canonical marking of Σ, P and Q are any two minimal dominating sets of vertices in Γ. Further, a signed graph $\Sigma = (\Gamma, \sigma)$ is called minimal dominating signed graph, if $\Sigma \cong MD(\Sigma')$ for some signed graph Σ'. The following result indicates the limitations of the notion $CMD(S)$ introduced above, since the entire class of unbalanced signed graphs is forbidden to be minimal dominating signed graphs.

Proposition 3.1. (Siva Kota Reddy and Prashanth, [**43**]) *For any signed graph $\Sigma = (\Gamma, \sigma)$, its minimal dominating signed graph $MD(\Sigma)$ is balanced.*

In this section, we offer a solution of the signed graph switching equivalence relation

$$CMD(\Sigma) \sim MD(\Sigma) \qquad (2)$$

in the sense that we determine the structure of all signed graphs satisfying (2). In case of graphs the following result due to S. M. Hosamani and B. Basavanagoud [**12**].

Proposition 3.2. (Hosamani and Basavanagoud, [**12**]) *Let $\Gamma = (V, E)$ be any connected graph and X be the set of all minimal dominating sets of Γ. Then $CMD(\Gamma) \cong MD(\Gamma)$ if, and only if, $\Gamma = K_p$ or Γ satisfies the following conditions:*

(1) *$|X| = |V|$ and $\Delta(\Gamma) \leqslant p - 1$*
(2) *each vertex v_i; $1 \leqslant i \leqslant p$ must be present in exactly n ($\geqslant 2$) number of minimal dominating sets of Γ.*

Proposition 3.3. *For any signed graph $\Sigma = (\Gamma, \sigma)$, $CMD(\Sigma) \sim MD(\Sigma)$ if, and only if, Γ satisfies the conditions of Proposition 3.2.*

Proof. Suppose $CMD(\Sigma) \sim MD(\Sigma)$. This implies, $CMD(\Gamma) \cong MD(\Gamma)$ and hence by Proposition 3.2, we see that the graph Γ must satisfies all the conditions of Proposition 3.2.

Conversely, suppose that Γ satisfies the all the conditions of Proposition 3.2. Then $CMD(\Gamma) \cong MD(\Gamma)$. Now, if Σ is a signed graph with underlying graph as mentioned under the conditions of Proposition 3.2, by Propositions 2.2 and 3.1, $CMD(\Sigma)$ and $MD(\Sigma)$ are balanced and hence, the result follows from Proposition 1.2. □

4. Switching Equivalence of $MD(\Sigma)$ and $L(\overline{\Sigma})$

The *line graph* $L(\Gamma)$ of a graph $\Gamma = (V, E)$ is that graph whose vertices can be put in one-to-one correspondence with the edges of Γ so that two vertices of $L(\Gamma)$ are adjacent if, and only if, the corresponding edges of Γ are adjacent. A given graph Γ is a *line graph*, if $\Gamma \cong L(\Gamma')$, for some graph Γ'.

Behzad and Chartrand [**3**] introduced the notion of line sigraph $L(S)$ of a given signed graph Σ as follows: Given a signed graph $\Sigma = (\Gamma, \sigma)$ its *line signed graph* $L(\Sigma) = (L(\Gamma), \sigma')$ is that signed graph whose underlying graph is $L(\Gamma)$, the line graph of Γ, where for any edge e_ie_j in $L(\Sigma)$, $\sigma'(e_ie_j)$ is negative if, and only if, both e_i and e_j are adjacent negative edges in Σ. Another notion of line signed graph introduced in [**7**], is as follows: The *line signed graph* of a signed graph $\Sigma = (\Gamma, \sigma)$ is a signed graph $L(\Sigma) = (L(\Gamma), \sigma')$, where for any edge ee' in $L(\Sigma)$, $\sigma'(ee') = \sigma(e)\sigma(e')$ (see also, E. Sampathkumar et al. [**21**]). In this paper, we follow the notion of line signed graph defined by M. K. Gill [**7**] as above. In [**7**], it was observed that for any signed graph Σ on the cycle C_n, $n \geqslant 3$, $L(\Sigma)$ is balanced. In [**2**], the author proved more generally, the following result:

PROPOSITION 4.1. (Acharya, [**2**]) *For any signed graph $\Sigma = (\Gamma, \sigma)$, its line signed graph $L(\Sigma)$ is balanced.*

In [**12**], the authors characterized graphs for which $MD(\Gamma) \cong L(\overline{\Gamma})$ as follows:

PROPOSITION 4.2. *For any graph Γ with $\Delta(\Gamma) < p-1$, $MD(\Gamma) \cong L(\overline{\Gamma})$ if, and only if, Γ satisfies the following conditions:*
(1) $\beta_0(\Gamma) = 2$
(2) *every minimal dominating set of Γ is independent.*

PROPOSITION 4.3. *For any signed graph $\Sigma = (\Gamma, \sigma)$, $MD(\Sigma) \sim L(\overline{\Sigma})$ if, and only if, Γ satisfies the conditions of Proposition 4.2.*

PROOF. Suppose $MD(\Sigma) \sim L(\overline{\Sigma})$. This implies, $MD(\Gamma) \cong L(\overline{\Gamma})$ and hence by Proposition 4.2, we see that the graph Γ must satisfies all the conditions of Proposition 4.2.

Conversely, suppose that Γ satisfies the all the conditions of Proposition 4.2. Then $MD(\Gamma) \cong L(\overline{\Gamma})$. Now, if Σ is a signed graph with underlying graph Γ satisfies the conditions: i). $\beta_0(\Gamma) = 2$; ii). every minimal dominating set of Γ is independent, by Propositions 3.1 and 4.1, $MD(\Sigma)$ and $L(\overline{\Sigma})$ are balanced and hence, the result follows from Proposition 1.2. □

The notion of *negation* $\eta(\Sigma)$ of a given signed graph Σ defined in [**10**] as follows: $\eta(\Sigma)$ has the same underlying graph as that of Σ with the sign of each edge opposite to that given to it in Σ. However, this definition does not say anything about what to do with nonadjacent pairs of vertices in Σ while applying the unary operator $\eta(.)$ of taking the negation of Σ.

Proposition 2.4, 3.3 & 4.3 provides easy solutions to other signed graph switching equivalence relations, which are given in the following results.

COROLLARY 4.1. *For any signed graph* $\Sigma = (\Gamma, \sigma)$, $N(\eta(\Sigma)) \sim CMD(\Sigma)$ *(or* $N(\Sigma) \sim CMD(\eta(\Sigma))$ *or* $N(\eta(\Sigma)) \sim CMD(\eta(\Sigma))$*) if, and only if,* Γ *satisfies the conditions of Proposition 2.3.*

COROLLARY 4.2. *For any signed graph* $\Sigma = (\Gamma, \sigma)$, $CMD(\eta(\Sigma)) \sim MD(\Sigma)$ *(or* $CMD(\Sigma) \sim MD(\eta(\Sigma))$ *or* $CMD(\eta(\Sigma)) \sim MD(\eta(\Sigma))$*) if, and only if,* Γ *satisfies the conditions of Proposition 3.2.*

COROLLARY 4.3. *For any signed graph* $\Sigma = (\Gamma, \sigma)$, $MD(\Sigma) \sim L(\eta(\overline{\Sigma}))$ *(or* $MD(\eta(\Sigma)) \sim L(\overline{\Sigma})$ *or* $MD(\eta(\Sigma)) \sim L(\eta(\overline{\Sigma}))$*) if, and only if,* Γ *satisfies the conditions of Proposition 4.2.*

Problem 4.4. Characterize signed graphs for which
i). $N(\Sigma) \cong CMD(\Sigma)$
ii). $CMD(\Sigma) \cong MD(\Sigma)$
iii). $MD(\Sigma) \cong L(\overline{\Sigma})$.

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